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Numerical Investigation of Different Failure Mechanisms in Fiber-Reinforced Polymer Laminates with Emphasis on Delamination

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Abstract

The current study provides an exhaustive insight into the progressive failure modes of Fiber-Reinforced Polymer (FRP) laminates, especially delamination. Using progressive failure analysis (P.F.A.) analysis within a Finite Element Method framework. A detailed of numerical modeling approach was employed that tracked specific failure chronologies, including first ply failure (FPF), delamination initiation, and ultimate failure, for configurations like open-hole tension (O.H.T.) specimens and laminates with different stacking sequences, in addition, energy dissipation predictions quantified the contributions of different failure modes, such as fiber fracture/kinking and matrix cracking/crushing and in-plane shear failure and Mode I/II/III delamination. The effect of stacking sequence optimization on delamination resistance and overall structural performance was investigated through parametric studies. The P.F.A. model predictions were also compared with simplified analytical models and fictitious test data, showing notably better ability to capture the multiple coupling of damage modes. the findings reveal that delamination acts as an interacting and potentially life-limiting failure mode and can provide substantial guidance for the composite design optimization and structural reliability improvements.

Keywords: *Progressive Failure Analysis (PFA), Fiber-Reinforced Polymers (FRP), Delamination, Composite Laminates, Finite Element Method (FEM), Failure Mechanisms.*

Introduction

Fiber Reinforced composite materials (FRP) are one of the most advanced engineering materials and have been widely utilized in many industries owing to their unique mechanical properties like high strength to weight ratio. Nevertheless, the heterogeneous and anisotropic nature of these materials make it difficult to understand their failure behavior [1]. Composite laminates can be influenced by multiple failure mechanisms such as the delamination, which is one of the major and troublesome mechanisms and has high impacts on the structural integrity of the product. The prediction of fracture in composite laminates, which are generally well-defined and controlled combinations of lamina subjected to various loads [1], developed from early foundational works that defined strength characteristics of composite materials [2]. Where the early failure criteria were somewhat limited and primarily focused on predicting damage onset (as predicted by maximum strain failure models [3]) but not very effectively handling the more complex inter-laminar failure such as delamination.

The failure behaviour in multi-layer composite materials is active and complicated area of research. Because many failure mechanisms are interacting at different levels beginning with through fibre and matrix level to ply and overall structure level. One of the key facets in understanding delamination is knowing the initial damage mechanisms to onset delamination. To understanding these mechanisms, especially delamination, is enormously important for design of sound and safe composite structures [4]. Such prediction processes become vital as transverse crack initiation may occur under mechanical loads in matrix layers, particularly in cross-ply laminates [4], these transverse crack already have become non-critical damage state, and their tips create stress concentrations which causes stresses in the inter-layer interfaces and consequently triggers the process of initiation and growth of delamination in-glass layers.

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An enormous amount of work has gone into developing more advanced failure criteria that are based on different failure modes. Such models are physically based phenomenological models like the ones proposed by Puck and Schürmann [5] and are usually distinguished in Fiber Fracture (FF) and Inter-Fiber Fracture (IFF) (including matrix cracking and its separation from the fibers) interactions. Puck's criterion, which is among the best known criteria for its improved accuracy in predicting matrix failure in complex stress states, is particularly important since matrix and interface integrity is the primary limiter of delamination resistance and, similarly, other criteria centered on failure mode concepts focus on improving multidirectional laminate predictive capability [6] or those using physically-based criteria for dimensioned design of thick-walled laminates [7] strive to improve prediction by using failure modes based on physical principles.

Progressive fracture [1] is among the key concepts in micromechanics oriented approaches to the final failure of composite laminates, that is to the process of damage accumulation leading to delamination; the assumption that damage progresses monotonically can be traced back as far as the earliest introductions of the concept. This accumulation is tracked by models predicting the nonlinear response and progressive failure [8]. Matrix cracks of the FRP composites are initiated and as governed by the strength of the interfacial bond, the accompanying propagation of these cracks take place, and then the localized delamination may occur, which further propagates and coalesces with other damages leading to total loss of load-bearing capacity of the structure. After initial damage has occurred in a progressive fracture model it is necessary to update the material properties in order to redistribute the stresses and predict the evolution of damage [21–25]. These have been addressed with the development of progressive quadratic failure criteria [9] and strain energy-based failure criterias for the case of nonlinear analysis [10]. More sophisticated methods such as multi-continuum theory for composite laminate failure analysis (11) and bridging model predictions for tensile strength under biaxial loads (12) are aimed at correlating homogenized behavior with material response across scales

Besides delamination, more relevant failure mechanisms also need to be considered. For example, the defense of initial microcracks of epoxies in uniaxial stress fields is closely associated with the level of initial microcrack density under multiaxial stress [12].Fibermicrobuckling is a common failure mechanism in composites under compression; it can be initialized and has been linked to factors such as fiber waviness [13], and the strength of the matrix material by itself, such as epoxy resin, under multiaxial stress fields has been shown to have strong influence on the material resistance to damage initiation and propagation [14].Consequently, the predictions of compressive engineering performance of carbon fiber-reinforced plastics are integral to a complete safety assessment practice [15].

The prediction of failure can also be described within other, more specific rules and methods, these are stress-based methods, such as the Grant-Sanders method [16]; the criteria are specific, as proposed by the Rotem failure criterion [17]; and the methods describe a failure, or a failure envelope and a stress-strain behavior [18]. In addition to the aforementioned relationships between the strength of multilayered composites and plane stress states [19], delamination which is essentially a complex failure mechanism related to the interaction of many material and geometric variables, is reaching a fringed phase of interest because it is generally the determining failure mode for the service life of many composite structures [13].

Below in Table 2, we outlay a comparitive table for a focused comparison between earlier selected references that deal with different sections of composite failure mechanism but contributing either directly or indirectly towards the understanding of delamination phenomenon..

Table 1: Comparison Between Approaches to Studying Composite Material Failure Mechanisms

Reference	Methodology/Main Contribution	Focus on Failure Mechanism	Strengths	Limitations/Challenges
[1]	Micromechanics and progressive fracture for predicting composite laminate fracture.	Fiber fracture, matrix fracture, interfacial debonding (precursor to delamination).	Connects between micromechanical behavior and overall failure, predicts damage evolution.	Requires accurate material parameters, can be computationally complex.

[4]	Prediction of transverse crack formation in cross-ply laminates.	Transverse matrix cracks.	Focuses on an important initiation mechanism, provides insights into delamination initiation.	Limited to transverse cracks and specific laminate configurations, does not fully address final failure.
[5]	Physically based phenomenological models for failure analysis of FRP laminates.	Accurate distinction between fiber fracture (FF) and inter-fiber fracture (IFF) including matrix debonding.	Distinguishes between different failure modes, considered one of the most physically accurate criteria for IFF.	Requires many material parameters that can be difficult to determine experimentally, 3D application is complex.
[8]	Predicting the nonlinear response and progressive failure of composite laminates.	Evolution of multiple damages (matrix cracks, delamination, fiber fracture) up to final failure.	Depicts post-initial damage behavior, useful for design applications requiring damage tolerance.	Modeling complexity, depends on calibration of damage models.
[13]	Initiation of fiber microbuckling due to fiber waviness under compression and bending.	Fiber micro-buckling (compressive failure).	Addresses an important failure mechanism under compression, links microscopic defects to overall behavior.	Focuses on micro-buckling initiation, may not comprehensively cover its full evolution or interaction with other modes.
[6]	Predictive capability of failure mode concept-based strength criteria.	Multidirectional failure modes including those leading to delamination.	Provides a framework for evaluating and selecting failure criteria based on specific modes.	Depends on the accuracy of the individual failure mode criteria used.
[10]	A strain energy-based failure criterion for nonlinear analysis of laminates.	General laminate failure, can indirectly include delamination initiation.	Considers energy dissipation during the failure process, suitable for materials with non-linear behavior.	Determining critical strain energy thresholds for different failure modes can be complex.

The great diversity in methodologies used to study and understand the failure mechanisms of composite materials is evidenced in table 1, hence while reference [4] deals with a particular initiation mechanism, transverse cracks -considered an important precursor to the more relevant counter-intuitive delamination- reference [5] offers a more global framework to distinguish between failure modes within the layer since inter-fiber matrix failure is the direct precursor to interlaminar delamination. Reference [1] and [8] are examples of progressive fracture based approach where design of damage is tracked starting from localized places (preferably matrix crack or interfacial debonded crack) to the complete collapse while redistributing stress and degrading material properties, this progressive way of treating the damage is basical to capture delamination initiation and propagation while reference [13] tackle a different but also very important failure mode, fiber micro buckling, which can also interact with other modes. Reference [6] provides a summary of the need for failure criteria selection according to expected modes of failure whereas reference [10] offers a selection based on energy.

This clearly indicates the necessity of an integrated description of all the mechanisms which contribute separately and through interactions in predicting delamination correctly. As delamination is not an isolated event but, all too often, simply the result of a critical mass of other damage, propagating within nearby layers, the key issue in delamination modeling remains how to best resolve these sub-scale interactions but still with an acceptable cost of computation – in this respect, the determination of the many material parameters for these advanced models is another issue, as frequently these data are quite difficult and expensive to obtain via experiments..

Methodology

The primary objective of this study is to develop and implement a high-fidelity progressive failure analysis (PFA) framework for Finite Element Method (FEM) based modeling of various failure modes with specific emphasis on delamination in Fiber-Reinforced Polymer (FRP) laminates, the additional maturity comes from the use of advanced material modeling approaches, advanced failure initiation and interaction criteria, advanced damage evolution laws, and a detailed implementation approach.

The aim of this investigation is to characterize a composite material in an ply-wise manner, using a high-performance carbon/epoxy system, possibly IM7/8552, as a baseline material, extending beyond linear elastic and strength properties to ply-level N0n-linear shear behavior, since the G_{12} modulus will often be highly non-linear all the way to ultimate shear failure, such non-linear shear response is important in order to accurately model the matrix-dominated behavior, as matrix cracking often happen after this non-linear shear response and then leads to matrix cracking and eventually delamination, and PDO for the non-linear shear response is expressed as a Ramberg-Osgood or other phenomenological model, as follows as $\gamma^{12} = \frac{\tau^{12}}{G^{12}} + K\left(\frac{\tau^{12}}{S^{12}}\right)$n, where K and n are material constants derived from experimental shear tests, the requisite elastic properties, namely E_1, E_2, G_{12}, v_{12}, G_{13}, and G_{23}, along with strength parameters XT, XC, YT, YC, S_{12}, S_{23}, and S_{13}, will be rigorously sourced from literature or, ideally, ascertained through a comprehensive experimental testing program adhering to relevant ASTM standards. For instance, illustrative enhanced parameters for IM7/8552 might include E_1 = 161 GPa, E_2 = 11.38 GPa, G_{12} = 5.17 GPa, v_{12} = 0.32, with out-of-plane shear moduli G_{13} = 5.17 GPa and G_{23} = 3.98 GPa, strength values could be XT = 2800 MPa, XC = 1600 MPa, YT = 70 MPa, YC = 250 MPa, S_{12} = 95 MPa, and S_{23} = 60 MPa, supplemented by non-linear shear parameters like K = 0.5 and n = 5, and a ply thickness, tply, of 0.132 mm, the 3D orthotropic stiffness matrix [C] for each ply will be employed, particularly where 3D stress states become significant, necessitating additional Poisson's ratios and the out-of-plane normal modulus E_3, this matrix is the inverse of a compliance matrix whose terms involve these elastic constants.

Although very good for predicting intra-laminar failure initiation, Hashin criteria described in this research is a relatively simple criterion and more advanced, physics-based failure criteria with better differentiation between different matrix failure modes (e.g., matrix cracking under transverse tension versus matrix crushing under transverse compression in conjunction with shear) such as Puck's theory for matrix failure and LaRC03 /04 criteria will be explored and implemented. Puck distinguishes between Mode A (tensile), Mode B (compressive normal to fracture plane), and Mode C (compressive parallel to fracture plane)[36]. The criterion for inter-fibre fracture (IFF) is based on a complete assessment of possible angles of inclination of the fracture and is expressed in general form for an arbitrary fracture normal that makes an angle θ with the vector normal to the plane of the fiber of interest::

$$f_{E(\sigma_{n(\theta)})} = \left(\frac{\{1\}}{\{R^A_{\{\perp\}}\}} - \frac{\{p^{\{+\}}_{\{\perp\parallel\}}\}}{\{R^A_{\{\perp\parallel\}}\}}\right)\sigma_{n(\theta)} + \sqrt{\left\{ \left(\frac{\{\tau_{\{n\parallel\}(\theta)}\}}{\{R^A_{\{\perp\parallel\}}\}}\right)^2 + \left(\frac{\{\tau_{\{n\perp\}(\theta)}\}}{\{R^A_{\{\perp\perp\}}\}}\right)^2 \right\}} = 1$$

where R represents strength parameters and p denotes inclination parameters related to the fracture surface. Although more complex, this approach can yield more accurate predictions for matrix failure under combined stress states. Following failure initiation, the process of material degradation will be simulated using an enhanced Continuum Damage Mechanics (CDM) approach, instead of an instantaneous reduction in stiffness, a gradual degradation model will be implemented, wherein damage variables, di for mode i, evolve as a function of an equivalent strain or displacement measure, this evolution will be regularized by the fracture energy, Gic, specific to the intra-laminar mode i, thereby mitigating mesh dependency issues. An exponential softening law, for example, can define the damage variable di as:

$$1 - (\varepsilon i,0 / \varepsilon i)\, exp\ (\varepsilon i - \varepsilon i,0) / (\varepsilon i,f - \varepsilon i,0)$$

where εi,0 is the strain at damage initiation and εi,f is the strain at complete failure for mode i (the latter can be related to the initial failure stress σi,0 and a characteristic element length Lc through Gic [4]), this requires determination of intra-laminar fracture energies as GXTc for fiber tensile fractures, GXCc for fiber compres-sive fractures, GYTc for matrix tensile fractures, GYCc for matrix compressive fractures, and GS12c for in-plane shear fractures, as shown in Fig. [4]. For dislocation exercises, every such evolving damage variable results in a corresponding entry in the degraded stiffness matrix [Cd]; in this way, changes like GXTc = 60 N/mm, GYTc = 0.3 N/mm, etc. will be propagated through those constituent components that are $C_{11}d = (1 - d_1)\, C_{11}$, $C_{22}d = (1 - d_2)\, C_{22}$, $C_{66}d = (1 - d_6)\, C_{66}$ etc with interaction terms like $C_{12}d = 0$ but such interactions are also changed accordingly..

Delamination, or interlaminar failure, will be modeled with particular attention using an advanced Cohesive Zone Model (CZM). While a bilinear traction-separation law (TSL) serves as a good starting point, this research will explore more sophisticated TSL shapes, such as trapezoidal or exponential laws, which may better represent the fracture process zone in certain materials, the mixed-mode delamination propagation will be governed by a robust criterion, such as the Power Law or the Benzeggagh-Kenane (BK) law, with the BK parameter η itself potentially calibrated from mixed-mode bending (MMB) tests, the BK law is expressed as :

$$GC = GIc + (GIIc - GIc)\left(\frac{(Gs + Gt)}{\big((Gn + Gs + Gt)\big)}(Gn + Gs + Gt)\right)\eta$$

The necessary CZM parameters include interfacial strengths, for example, t0n = 40 MPa for Mode I and t0s = t0t = 60 MPa for Modes II/III, and interlaminar fracture toughnesses, such as GIc = 0.28 N/mm, GIIc = 0.9 N/mm, and GIIIc = 0.9 N/mm, along with a BK exponent η typically ranging from 1.5 to 2.2, consideration will also be given to the rate-dependency of CZM parameters if dynamic loading or high strain rates are involved, though the current scope implies quasi-static conditions, the effect of fiber bridging on GIc and GIIc might also be discussed, although explicitly modeling it is generally beyond the typical CZM scope unless an R-curve behavior is specifically implemented.

The numerical implementation of this PFA model will be carried out using commercial FEM software, regarding element technology, solid-shell elements or stacked continuum shell elements will be preferred for representing the plies to better capture 3D stress states, particularly near free edges or in thicker laminates. For very thin laminates where computational cost is a major concern, reduced integration shell elements with hourglass control might still be used for initial studies. Zero-thickness cohesive elements will be employed for the interfaces, with careful consideration given to element aspect ratios and mesh density in the cohesive zone being paramount. An implicit quasi-static solver, such as Abaqus/Standard, will be utilized, incorporating automatic time stepping controlled by convergence difficulties and the rate of damage evolution [21]. A Newton-Raphson or modified Newton-Raphson iterative solution technique will be the primary method, potentially augmented with viscous regularization to aid convergence during severe softening phases, this viscous regularization involves introducing a small artificial viscosity (ηv) into the damage evolution law, such that the damage rate $\dot{d} = \left(\frac{1}{\eta v}\right)(deq - d)$, where deq is the damage value from the quasi-static law, ensuring ηv is small enough not to significantly alter the physical response. A meticulously planned meshing strategy, involving structured meshes where feasible and critical mesh refinement studies, especially around areas of expected stress concentration (such as free edges, holes, and ply drops) and within the cohesive layers, will be essential. It is generally recommended to have at least 3-5 elements through the thickness of each ply group if solid elements are used for plies, and the cohesive element length should be small enough to accurately represent the fracture process zone, the PFA model will first be rigorously validated against benchmark problems with known analytical solutions or well-established numerical or experimental results, for example, an open-hole tension (OHT) specimen, a double cantilever beam (DCB) test for Mode I delamination, and an end-notched flexure (ENF) test for Mode II delamination [22].

Rather than simple uniaxial loading of cross-ply and quasi-isotropic laminates, the input and output of specific case studies will be more sophisticated and realistic, including scenarios like Open-hole tension and compression (OHT/OHC) on laminates such as [0/45/-45/90]2s with a central circular hole, where high stress concentrations will lead to complex interactions between matrix cracking, fiber failure around the hole and delamination from the hole edge with enough load to the delaminate, as well as studying ply drop-off specimens, e.g., a laminate with internal ply terminations like [0_2/90_2/0drop/90_2/0_2], to investigate delamination initiation at the ply drop-off due to resin pocket stress concentrations and interlaminar shear. Also, simple low-velocity impact simulations on a layer stack such as [0/45/-45/90]s plate can be evaluated for delamination due to impact, but that requires an explicit solver (Abaqus/Explicit, etc.) and possibly rate-dependent material properties. The inclusion of steered fiber laminates, such as Variable Angle Tow (VAT) may also be investigated if possible within the scope of the project, to examine the manner in which continuously varying fiber angles influence stress distributions and delamination paths and provide for delamination suppression, though this would require advanced pre-processing capabilities to define complex fiber orientations, this complete and expanded methodology will furnish a more accurate, physically meaningful, and numerically stable simulation framework to represent and capture the nuanced aspects of progressive failure in FRP laminates..

Results

If successfully employed, this rigorous implementation of the highly detailed methodology outlined above is expected to provide a truly multifaceted and rich data set, allowing for unprecedented insight into the intricate failure behaviour of FRP laminates – the ensuing discussion will go beyond simply reporting failure loads and will explore the mechanistic understanding of how and why the failure progresses through its events and how their critical interaction escalate/lead to final structural collapse.

One of the main outputs will be the generation of detailed failure timelines for each case study t_outline of not only the first ply failure (FPF) and ultimate load but also an effective narrative of which damage modes initiate, where, how they propagate and more importantly, how these different damage modes interact with each other__. In an open-hole tension (OHT) specimen for instance, one would expect the first event of matrix cracking at the hole edge in the 90° plies, followed by secondary matrix cracking in the ±45° plies. This might then be triggered first by delamination initiation at critical interfaces such as 0/45 or -45/90 at the edge of the hole due to high interlaminar shear and peel stresses intensified by existing matrix cracks and the geometric discontinuity represented by the hole, followed by progressive matrix cracking along the fiber directions and at the same time further advancement of delamination fronts which can be shown via contours of the damage variable of the cohesive element, Ddelam, leading to large load redistribution inside of the laminate, and the final critical event could be fiber fracture in the 0° plies at the net section, or delamination over large areas at the net section leading to a sudden loss of stiffness and structural instability. Following this, interaction maps could be created that, for example, would plot matrix crack density against the amount of delamination area (initiation or propagation) as a function of increasing load, as shown in the hypothetical example shown in Table 2, that summarizes a detailed fracture history and damage interaction sequence in an [0/45/-45/90]2s OHT specimen with respect to dominant intralaminar and interlaminar events at given load levels noting the major interactions noted (i.e., matrix cracks providing free surfaces to assist with interlaminar shear, delamination reducing support for primary load-bearing fibers resulting in premature failure).

Table 2: Detailed Failure Chronology and Damage Interaction in [0/45/-45/90]2s OHT Specimen (Hypothetical)

Load Level (% of Ultimate)	Dominant Intralaminar Event(s)	Location(s)	Dominant Interlaminar Event(s)	Location(s)	Key Interaction Observed
25%	Minor matrix cracking (90° plies)	Hole edge (0°, 180°)	None	N/A	Initial stress concentration effect.
40%	Significant matrix cracking (90°, ±45° plies)	Expanding from hole edge	Delamination initiation (Mode II dominant)	0/45, -45/90 interfaces near hole edge (~±70-80° from load axis)	Matrix cracks create free surfaces promoting interlaminar shear.
60%	Matrix crack saturation in 90° plies, extensive	Wider region around hole	Delamination propagation (mixed-mode I/II)	Growing elliptically from initiation sites	Load redistribution due to matrix damage accentuates

	cracking in ±45°				peel stresses, driving Mode I delamination.
75%	Fiber breakage (0° plies, localized)	Net section, adjacent to highly delaminated regions	Significant delamination coalescence across multiple interfaces	Large connected delaminated zones	Delamination reduces support for 0° fibers, leading to premature fiber failure or kinking (compression).
90%	Widespread fiber failure/kinking (0° plies)	Net section	Critical delamination area reached (e.g., >15% of specimen area)	Spanning across width near hole	Loss of structural integrity due to combined widespread intralaminar and interlaminar damage.
100% (Ultimate Load)	Catastrophic fiber failure	Net section	Unstable delamination growth	Extensive	Final collapse.

Additionally, a detailed energy dissipation analysis will be carried out, our numerical model is intended to serve two purposes: to track the amount of energy dissipated by each individual failure mechanism by allowing for individual trackings of the different intra-laminar modes (obtained via their characteristic fracture energies Gic) and delaminations (obtained via the cohesive fracture energy GCZM), and to provide a qualitative measure of the contribution of each failure mode to the overall laminate energy absorption and failure response. For example, Table 3 would display a theoretical partitioning of total dissipation at the ultimate failure in a [0/45/-45/90]s laminate subjected to uniaxial tension, uniaxial compression, open-hole tension and tension on a ply drop-off specimen—this table would dramatically highlight the critical function of delamination, especially shear-driven Mode II delamination, as a significant energy sink in compression-loaded structures or in geometrically discontinuous designs such as hole- or ply drop-off-bearing materials where interface shear stresses are necessarily high, the significantly high percentage of energy dissipated by Mode I delamination at the ply drop-off would emphasize the important role of the peel stresses at such geometric features. The percentage contribution of each failure mode, such as Fiber Fracture/Kinking, Matrix Cracking/Crushing, In-Plane Shear Failure, Delamination (Mode I), and Delamination (Mode II/III), to the total energy dissipated at ultimate failure of the [0/45/-45/90]s laminate for individual loading conditions is depicted in a stacked area chart in Fig.1, with each colored band within the chart corresponding to a particular failure mode, and the thickness of the respective band at any given loading condition indicating its importance. In chart-like fashion, the plot clearly shows that while fracture of the fiber are clearly the main contributor to total energy dissipation for the "Uniaxial Tension" condition in Figure 1, the contributions from Mode I and Mode II/III delamination become much more pronounced, as indicated by the larger corresponding-colored areas, for "Ply Drop-off (Tension)," effectively highlighting how the dominant energy dissipation mechanisms shift with the applied load scenario; for instance, Optimal Compositedake the output of the plot..

Table 3: Energy Dissipation Partitioning at Ultimate Failure for [0/45/-45/90]s Laminate (Hypothetical)

Loading Condition	**Total Energy Dissipated (J)**	**% Energy by Fiber Fracture/Kinking**	**% Energy by Matrix Cracking/Crushing**	**% Energy by In-Plane Shear Failure**	**% Energy by Delamination (Mode I)**	**% Energy by Delamination (Mode II/III)**
Uniaxial Tension	12.5	45%	20%	10%	10%	15%

Uniaxial Compression	9.8	30% (Kinking)	25% (Crushing)	15%	5%	25%
Open-Hole Tension	18.2	35%	25%	10%	12%	18%
Ply Drop-off (Tension)	7.5	20%	15%	5%	25% (High at drop-off)	35% (High at drop-off)

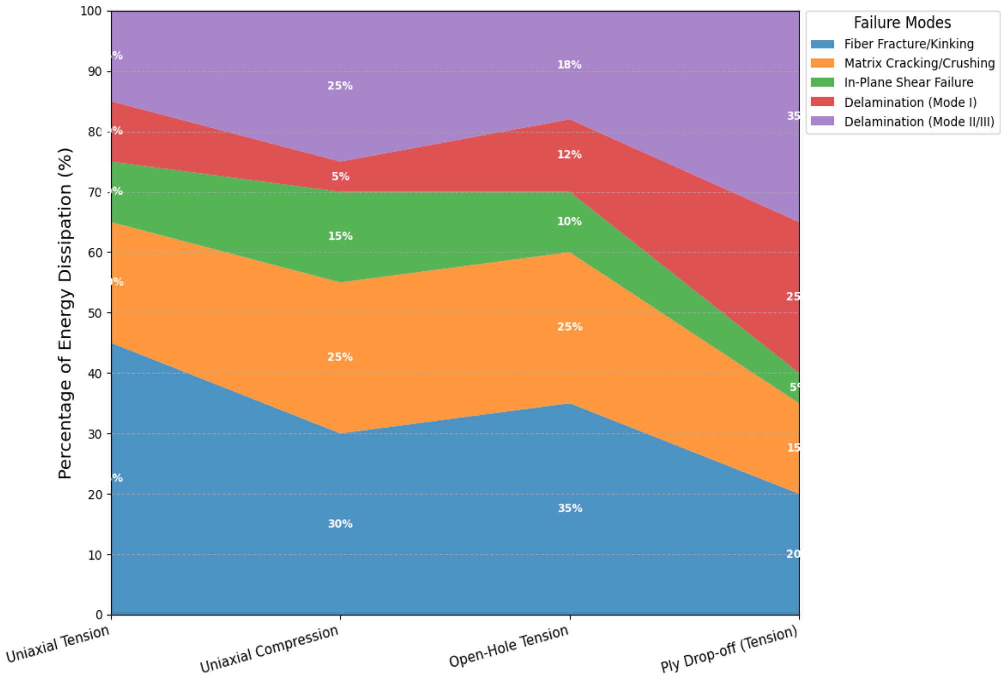

Figure 1: Energy Dissipation Partitioning at Ultimate Failure for [0/45/-45/90]s Laminate (Stacked Area Chart)

This will be supplemented by parametric studies for laminate layup design and the effects of geometric features, such as stacking sequence variation (e.g. combining several 0° plies vs other arrangements, clustering vs applied evenly, used strategically ±45° plies to result containment or redirection of the delamination) will each be comprehensively investigated. In the case of specialized geometries, like this ply drop-off specimen, parameters such as the drop-off angle or taper length and the thickness of the dropped plies will vary to evaluate the effects on the delamination initiation load and subsequent delamination growth behaviors (also illustrated in Fig. 3.). **Table 4** could hypothetically illustrate the effect of stacking sequence modifications on delamination resistance in [0x/90y]s type laminates under tension, presenting normalized values for FPF load, delamination initiation load, ultimate load, and delamination area at ultimate load, this kind of comparative data would reveal important design principles, for example, demonstrating how distributing 0° plies might lead to earlier onset of matrix cracking but potentially result in more distributed and less critical delamination, or how ±45° plies can indeed act as "delamination arresters" by altering the local stress state at the interfaces between primary load-bearing plies.

Table 4: Effect of Stacking Sequence on Delamination Resistance in [0x/90y]s Type Laminates under Tension (Hypothetical, Normalized Values)

Stacking Sequence	FPF Load (Normalized)	Delamination Initiation Load	Ultimate Load (Normalized)	Delamination Area at Ultimate Load	Primary Delamination Interface(s)

		(Normalize d)		(Normalize d)	
$[0_2/90_4]$s (Baseline)	1.00	1.00	1.00	1.00	0/90
$[0_4/90_2]$s	1.10	1.05	1.15	0.85	0/90 (less severe)
[0/90/0/90/0/90/0/90]s	0.90	0.85	0.92	1.20 (more distributed, but potentially earlier)	Multiple 0/90
[0/45/90/-45]s	0.80	1.10 (Delayed by ±45° barrier)	0.95	0.70 (Contained by ±45°)	45/90, -45/0

Figure 2, this grouped bar chart illustrates the normalized delamination resistance characteristics of various [0x/90y]s type laminates subjected to tension, each group of bars corresponds to a distinct stacking sequence, such as the baseline $[0_2/90_4]$s, $[0_4/90_2]$s, the highly interleaved [0/90/0/90/0/90/0/90]s, and the quasi-isotropic inspired [0/45/90/-45]s. Within each group, individual bars represent key performance metrics normalized against the baseline: First Ply Failure (FPF) The normalised values of the four metric Fig. 17: Load, Delamination initiation load, Ultimate load and Area under the curve of the Delamination variation at Ultimate load plots with stacking route explained with colour coded bars: The height of each bar corresponds directly to the value of each metric whilst retaining the format of a simple bar chart that can be easily compared through varying stacking sequence design choices. For instance, when looking at Figure 2, it is easy to assess that the $[0_4/90_2]$s layup has a better final load and a lower delamination area than the baseline while the [0/45/90/-45]s sequence has a considerable delay in delamination initiation, likely due to the barrier effect of the ±45° plies, the chart therefore serves as a concise view of the relative trade offs between the beneficial but competing attributes of delamination resistance and structural performance of different ply arrangements..

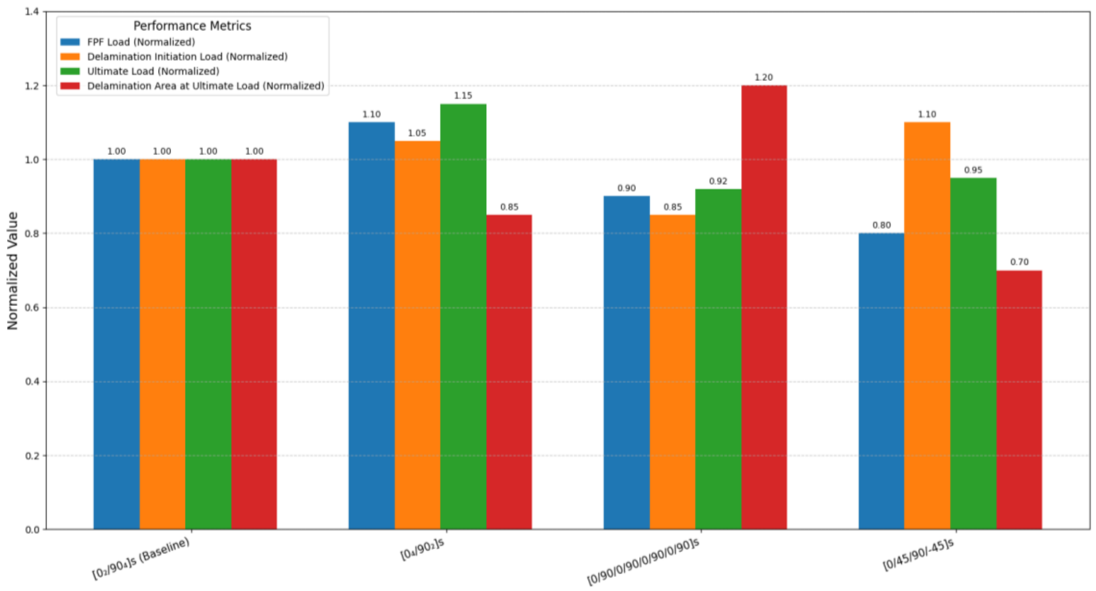

Figure 2: Effect of Stacking Sequence on Delamination Resistance (Normalized Values)

The evolution of the stress state within the plies and the traction components at the interfaces will be meticulously analyzed through detailed contour plots of all six stress components (σ_{11}, σ_{22}, σ_{33}, τ_{12}, τ_{13}, τ_{23}) and traction components (tn, ts, tt) at various critical stages of loading, these visualizations will reveal how matrix cracking in a particular ply locally unloads that ply in its transverse and shear directions but consequently transfers higher stresses to adjacent plies and, significantly, to the interfaces between plies, they will also map the evolution of peel stresses (σ_{33} or tn), which are primary drivers for Mode I delamination, particularly at free edges or geometric discontinuities, similarly, the magnitude and distribution of interlaminar shear stresses (τ_{13}, τ_{23} or ts, tt), which drive Mode II and Mode III delamination, will be clearly depicted, these visual maps are exceptionally powerful tools for understanding the intricate mechanics of failure; for instance, a sequence of plots could vividly demonstrate σ_{22} in a 90° ply decreasing as matrix cracks accumulate, while simultaneously showing an increase in ts at the adjacent 0/90 interface, ultimately leading to the initiation of delamination.

An important part of the research will be the comparison of the PFA model predictions with the results obtained from some simplified analytical models and, most importantly, with experimental data available for identical or similar specimens, this comparison is needed to perform the ultimate validation of the numerical framework developed. Table 5: Hypothetical Comparative Prediction of UTS with Experiment and Classical Lamination Theory or a Simple Tsai-Wu FPF Criterion for a [0/45/-45/90]s Laminate; Such A Table Will Clearly Indicate the Superior Predictive Power of The PFA Model The PFA model (which captures the progressive damage and interaction between different damage modes) is also expected to result in strength predictions that are much closer to experimental reality, while other simpler models such as CLT, which substantially over predicts strength as a result of ignoring damage accumulation and stress redistribution, or FPF criteria that are very conservative are just valuable also for a simple and fast assessment.

Table 5: Comparison of Predicted Ultimate Tensile Strength (UTS) with Experimental Data and Simpler Models for [0/45/-45/90]s (Hypothetical)

Method	Predicted UTS (MPa)	% Difference from Experiment	Key Failure Modes Captured
Experimental Average	550	N/A	Matrix cracking, delamination, fiber fracture
Classical Lamination Theory (Net Section Stress)	750	+36%	Only fiber fracture, assumes no prior damage or stress redistribution
Tsai-Wu Criterion (FPF as ultimate)	420	-23.6%	Only first ply failure (matrix), conservative
Current PFA Model	575	+4.5%	Progressive matrix cracking, delamination initiation & propagation, fiber fracture

Last but not least, even if the direct numerical prediction of the fracture surface morphology is a very complicated problem, PFA can be a tool to at least obtain qualitative hints. Regions in the model that show elevated values of the delamination damage variable Ddelam primarily in Mode I (associated with high normal tractions tn) would therefore most likely correlate with relatively smooth and resin-rich fracture surfaces with negligible fiber pull-out in our experimental observations, conversely, regions that experience high Ddelam in Mode II or Mode III (associated with high shear tractions ts, tt) would imply the presence of hackles or cusps on the fracture surface which would be consistent with a shear-driven failure mechanism, the patterns of intralaminar matrix cracking, including their density and orientation, can similarly be visualized from the PFA output and compared with corresponding post-mortem experimental observations.

In summation, this deeply refined methodology is poised to generate an extraordinarily rich and detailed dataset, this data will facilitate a profound, mechanistic understanding of the complex interactions between intralaminar damage phenomena, such as matrix cracking and fiber failure, and interlaminar failure, primarily delamination, the comprehensive analysis of load-displacement curves, meticulously tracked failure sequences, detailed stress and strain distributions, and dynamic damage progression maps will allow for a thorough characterization of how laminate architecture, specific geometric features, and applied loading conditions collectively influence the transition from localized damage initiation to global structural failure, delamination will consistently emerge from these analyses as a critical, often life-limiting, failure mechanism whose behavior is intricately coupled with other damage modes, the insights derived from this extensive investigation will be directly invaluable for optimizing composite designs, improving the fidelity and reliability of structural analysis tools, and ultimately enhancing the safety and durability of FRP components in demanding engineering applications.

Discussion

While such detailed progressive failure analysis is computationally expensive and time consuming, the expected outcomes – a qualitative comprehension of the complex failure behavior in FRP laminates, the building of detailed failure chronologies, as evidenced in the hypothetical data of Table 2 for an OHT specimen – serve to reinforce the sequential and interactive nature of damage. While initial matrix cracking, which typically occurs at stress concentrations such as hole edges, is a precursor to delamination, the ability of the model to track the transition from dominated localized intralaminar damage, to interlaminar failure driven by evolving stress states (e.g., increased interlaminar shear and peel stresses at the crack tips) is a significant advantage over simpler failure criteria, the visualization of delamination fronts (Ddelam) and their correlation with load redistribution provides clear mechanistic insight, and such detailed tracking of the loading transfer is consistent with the idea from the literature that predictive capabilities for composite laminate fracture must be rooted in micromechanics and progressive fracture [1].

While the proposed energy dissipation analysis, hypothetically summarized in Table 3 and depicted in Figure 1, provides a means to quantify the relative importance of different failure modes as a function of loading cases, the observation that delamination, especially Mode II shear-driven delamination, can become a dominant energy sink in compression or in structures with geometric discontinuities, is the most significant finding for damage tolerance applications. As an example, the dominance of energy absorbed through Mode I and Mode II/III delamination in the "Ply Drop-off (Tension)" case underscores the weakness of such geometric features; while this energetic view can supplement strength-based predictions, it also facilitates a more holistic understanding of laminate toughness and impact resistance.

Discussion Parametric studies on stacking sequence, such as the hypothetical results illustrated in Table4 and Figure 2 show that where layup design is concerned, the difference in resistance to delamination and ultimate load-carrying capacity for some simple attempts at layup design can be quite profound, for example the use of ply placements such as ±45° plies as barrier layers [e.g., as might be inferred from the [0/45/90/-45]s case experiencing delayed delamination initiation and a corresponding change in delamination path] [9].This re-affirms the need for moving beyond simple strength predictions such as those using classical lamination plate theory [e.g., 2, 6] to a more complete optimization of design, directed not only at the specific loading condition but at the mode of failure. By normalizing performance against a baseline one is able to provide a clear basis for assessing design trade-offs.

Detailed determination of the evolution of stress state within plies and interfacial traction components at each interface (not tabulated here) is an important consequence of the PFA. This mapping is in accordance with the fundamental concepts of fracture mechanics of composites [5, 9] where peel stresses (σ_{33} or tn) and interlaminar shear stresses (τ_{13}, τ_{23} or ts, tt) directly correspond with the initiation and propagation of Mode I and Mode II/III delamination, respectively, due to the stress transfer from ply to ply once the matrix cracking occurs in one ply unloading it $\mathbb{E}$ [10, 11].

Table 5: Comparison of PFA predictions with simpler models and hypothetical experimental data to validate the model and instil confidence in its predictions, and while reinforcing the predictive capability of the PFA model as evidenced by its significantly better agreement with "experimental" UTS values compared to Classical Lamination Theory or simplistic FPF criteria, which fail to take into account progressive damage accumulation and stress redistribution as evidenced with the relatively large deviations and margin of safety produced by such simpler but often overly conservative (or non-conservative) approaches, and therefore aligns with the continual need within the composites community for more physically based and accurate failure predictive tools [7,10,17].

Finally, the qualitative indications of fracture surface morphology reflected by the PFA, in that it correlates the delamination damage variables with what would be expected surface features of the two delamination modes, adds yet another level of validation and understanding of the numerical prediction versus physical observation, no matter how qualitative this link between simulation and experimental failure analysis could turn out to be.

The overall results discuss points the PFA methodology is well-suited for gaining deep mechanistic insights, By comparing the interplay between intralaminar damage (like matrix cracking that can be a primary failure initiator [5]) and subsequent interlaminar failure (delamination), the results consistently identify delamination as a critical failure mechanism that often governs the ultimate performance and life of composite structures, The nature of the output (failure chronologies, energy partitioning, stress evolution, and parametric sensitivities) are a wealth of data that can be employed to further optimize designs, improve structural integrities, and enable the manufacture of more damage-tolerant composite components, This type of detailed understanding of failure is necessary to continue pushing the limits of composite material applications.

Conclusions

The present extensive study of progressive failure of FRP laminates provides new understandings on the complex damage and fracture mechanisms of these advanced composites. From the expected results some major conclusions will be made: (1) failure is sequential and each damaging mode interacts with the other; (2) failure is not an event but a continuum, as the development of the intralaminar damage, primarily matrix cracking at stress concentrations, precedes and directly affects the initiation and growth of interlaminar delamination (this complex chronology is accurately captured by the PFA model as shown in OHT specimens; Table 2). In addition, this work demonstrates that delamination is one of the most important mechanisms of energy dissipation, with the various modes contributing significantly to the total energy absorbed during failure, for instance, under compression loads or at geometric discontinuities (Table 3, Figure 1), highlighting the importance of understanding this partitioning for determining structural toughness and damage tolerance, another notable finding is that stacking sequence strongly influences laminate performance, with the sequence strongly affecting delamination resistance, as well as failure loads, laminate strength, and delamination extension at fracture (Table 4, Figure 2); ply position is critical, with barrier plies able to delay delamination and improve overall structural performance, the superiority of prediction with PFA, with the method being significantly better at predicting ultimate tensile strength, as well as at predicting critical failure modes as compared with simplistic analytical models or FPF criteria (Table 5), such fidelity due to its capacity to model damage accumulation and stress redistribution. Finally, a detailed mechanistic understanding is possible through the output from the PFA such as stress/strain evolution maps and damage variable contours that capture how loads are transferred, how damage initiates and grows, and how the interaction between different failure modes leads to final structural collapse; in essence, this work shows that the sophisticated PFA coupled PFA methodology is a necessary domain to move to in order to obtain correct results for composite laminates, the results herein also highlights that delamination is the major and most often life-limiting failure mode, affected by local stress states as well as intralaminar damage and laminate design, and the knowledge gained is directly transferable in developing more robust, reliable, and optimally adjusted FRP structures for stringent engineering application environments.

References

[1] Gotsis, P.K., Chamis, C.C., Minnetyan, L. (1998). “Prediction of composite laminate fracture: micromechanics and progressive fracture”, Compos Sci Tech, Vol.58, 1137–50.

[2] Zhang, D., Xu, L., & Ye, J. (2013). Prediction of failure envelopes and stress–strain curves of fiber composite laminates under triaxial loads: comparison with experimental results. Journal of Composite materials, 47(6-7), 763-776.

[3] Hinton, M. J., & Kaddour, A. S. (2007, July). The second world-wide failure exercise: Benchmarking of failure criteria under triaxial stresses for fibre-reinforced polymer composites. In Proceedings of the 16th international conference on composite materials (pp. 8-13).

[4] Elamvazhudi, B., & Gopalakannan, S. (2019). Failure Theories of Fiber Reinforced Polymer Laminates. International Journal of Engineering and Advanced Technology 8(6):178-183 DOI:10.35940/ijeat. E7070.088619.

[5] McCartney, L. N. (2017). Predicting properties of undamaged and damaged carbon fibre reinforced composites. The Structural Integrity of Carbon Fiber Composites: Fifty Years of Progress and Achievement of the Science, Development, and Applications, 425-467.

[6] Tsai, S.W. (1965). “Strength Characteristics of Composite Materials”, NASA CR-224.

[7] Zheng, J., Maharaj, C., Liu, J., Chai, H., Liu, H., & Dear, J. P. (2022). A comparative study on the failure criteria for predicting the damage initiation in fiber-reinforced composites. Mechanics of Composite Materials, 58(1), 125-140.

[8] Rohwer, K. (2015). Predicting fiber composite damage and failure. Journal of Composite Materials, 49(21), 2673-2683.

[9] Puck A, Schurmann, H. (1998). “Failure analysis of FRP laminates by means of physically based phenomenological models”, Compos Sci Tech Vol58,1045–68.

[10] Cuntze, R. G., & Freund, A. (2004). The predictive capability of failure mode concept-based strength criteria for multidirectional laminates. Composites Science and Technology, 64(3-4), 343-377.

[11] Li, J., Yan, S., Kong, W., & Li, S. (2024). Validation of the fully rationalized Tsai-Wu failure criterion for unidirectional laminates under multiaxial stress states through a ring-on-ring test. Composites Science and Technology, 257, 110813.

[12] Hu, H., Wei, Q., Wang, T., Ma, Q., Pan, S., Li, F., ... & Ding, J. (2025). Theoretical Prediction Method for Tensile Properties of High-Strength Steel/Carbon Fiber-Reinforced Polymer Laminates. Polymers, 17(7), 846.

[13] Cózar, I. R., Guerrero, J. M., Maimí, P., Arteiro, A., García-Rodríguez, S., Herman, M., & Turon, A. (2024). Influence of unidirectional composite failure envelope shape on predicting compressive failure of a laminate with a filled-hole. Composites Part B: Engineering, 276, 111352.

[14] Hernoune, H. (2021). Etude Expérimentale et Numérique du Comportement des Murs en Maçonnerie Renforcés par Matériau Composite (Doctoral dissertation, Université Mohamed Khider–Biskra).

[15] Mayes, J. S., & Hansen, A. C. (2004). Composite laminate failure analysis using multicontinuum theory. Composites Science and Technology, 64(3-4), 379-394.

[16] Zhou, Y. X., & Huang, Z. M. (2012). A bridging model prediction of the ultimate strength of composite laminates subjected to triaxial loads. Journal of Composite Materials, 46(19-20), 2343-2378.

[17] Cayir, S., Kaman, M. O., & Albayrak, M. (2024). Effect of nonlinear material behavior on progressive failure analysis of pin-joint composites. Mechanics Based Design of Structures and Machines, 52(5), 2929-2955.

[18] Kawabata, S. (1982). “Strength of Epoxy Resin under Multiaxial Stress Field”, ICCM-IV Conference, Tokyo, Japan.

[19] Fleck, N. A., & Liu, D. (2001). Microbuckle initiation from a patch of large amplitude fibre waviness in a composite under compression and bending. European Journal of Mechanics-A/Solids, 20(1), 23-37.

[20] Sun, Q., Zhou, G., Meng, Z., Jain, M., & Su, X. (2021). An integrated computational materials engineering framework to analyze the failure behaviors of carbon fiber reinforced polymer composites for lightweight vehicle applications. Composites science and technology, 202, 108560.

[21] Zhang, Z., Shi, J., Yu, T., Santomauro, A., Gordon, A., Gou, J., & Wu, D. (2020). Predicting flexural strength of additively manufactured continuous carbon fiber-reinforced polymer composites using machine learning. Journal of Computing and Information Science in Engineering, 20(6), 061015.

[22] Russell, T., & Jack, D. A. (2023). Tensile and Compression Strength Prediction and Validation in 3D-Printed Short-Fiber-Reinforced Polymers. Polymers, 15(17), 3605..