



Predicting behavior due to interlayer separation in composite materials using artificial intelligence tools

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ABSTRACT

This study develops a computational framework to predict the evolution of matrix cracking and the resulting interlaminar delamination in cross-ply composite laminates subjected to in-plane loading. By combining meso-macro multiscale modeling with continuum damage mechanics (CDM), an integrated approach is proposed to evaluate progressive damage in composite structures. The methodology employs quasi-simultaneous multiscale analysis, advanced finite element simulations, and image-processing-assisted machine learning to accurately characterize the initiation and propagation of matrix cracks and delamination. To quantify the influence of matrix cracking and interlaminar separation on the nonlinear response of multilayer laminates, a simplified AI-based formulation is developed to compute damage parameters linked to matrix cracking and induced delamination. A CDM-based user subroutine is implemented in the finite element environment to simulate the gradual evolution of transverse cracks, fiber breakage, and interlayer separation, enabling prediction of the ultimate failure load under monotonic loading. The accuracy of the proposed computational model is validated against available experimental datasets. The predicted stress-strain curves, damage chronology, and failure patterns show excellent agreement with experimental observations, confirming the method's ability to capture intralaminar and interlaminar damage mechanisms simultaneously in composite laminates.

Introduction



Composite materials are engineered by combining two or more constituents—typically high-strength fibers and a polymeric matrix—to achieve superior mechanical and functional properties. These materials exhibit high specific strength and stiffness, excellent corrosion resistance, and design flexibility, making them widely used in aerospace, automotive, marine, and biomedical industries [1]. The mechanical performance and durability of composite laminates are strongly influenced by their failure mechanisms, which may include matrix cracking, microcracking, transverse cracking, fiber breakage, and interfacial debonding.

To evaluate the effect of matrix cracking on the mechanical response of composite structures, several crack-density-based formulations have been proposed that relate stiffness degradation to the density of transverse cracks. Continuum damage mechanics (CDM) provides a powerful theoretical basis for modeling such nonlinear degradation processes, and numerous studies have applied CDM to simulate various failure modes in laminated composites [2].

Among the primary damage mechanisms, matrix cracking and interlaminar delamination play dominant roles in degrading structural performance under mechanical loading. These damages modify the local stress distribution, accelerate crack coalescence, and ultimately trigger global failure. Although several numerical techniques—such as the virtual crack closure technique (VCCT), cohesive zone models, 3D Hashin criteria, and the Ladevèze CDM model—have been used to simulate delamination, relatively few studies have addressed the fully coupled progressive evolution of matrix cracks and delamination within a unified framework [3].

Recent advances in quasi-simultaneous multiscale modeling have significantly improved the capability to capture the interplay between micro-level damage and meso-level laminate behavior. These methods achieve accurate predictions of stiffness degradation and failure initiation while reducing modeling complexity [4].

However, challenges remain regarding computational cost, the need for extensive experimental calibration, and the difficulty of modeling the complex interaction of multiple damage modes.

To overcome these challenges, this study introduces an artificial intelligence-enhanced multiscale modeling approach for predicting matrix cracking and interlayer delamination. Machine learning algorithms are incorporated to detect delamination, interpret image-based damage features, evaluate crack density, and compute corresponding damage parameters with high accuracy. This approach enables reliable representation of nonlinear

stress fields, crack evolution, and stiffness degradation at different scales, even when experimental data are limited [5].

The objective of this research is therefore twofold: To develop an AI-augmented meso-macro multiscale model for predicting interlaminar delamination alongside intralaminar failure mechanisms. To implement a CDM-based user subroutine in ANSYS capable of simulating progressive damage—including matrix cracking, fiber breakage, and delamination—under general in-plane loading.

The proposed framework is validated through comparison with experimental results for open-hole cross-ply laminates, demonstrating its ability to accurately predict stress-strain behavior, damage chronology, and ultimate failure patterns.

Methodology

Characteristic Element Homogenization

When a composite element is subjected to in-plane loading, each layer may experience distinct failure mechanisms depending on its orientation, material properties, and local stress distribution (Figure 1). Typical failure modes include transverse matrix cracking, fiber breakage, and interlayer delamination, which can interact to influence the overall structural response [6].

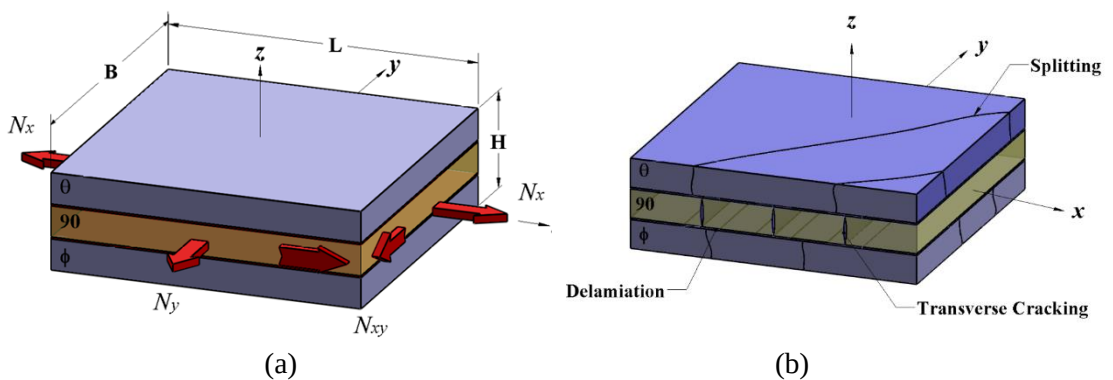


Figure 1. (a) Characteristic element intact or damaged under in-plane loading, (b) Characteristic element containing possible failure mechanism states at different layers.

Matrix cracks in one layer—particularly in 90° plies or off-axis plies (θ)—can induce interlayer separation at the interface between adjacent layers. This interlayer delamination alters the stress-transfer mechanism, contributing to

the progressive degradation of the laminate stiffness. To model this phenomenon, this study introduces a homogenized representation of the damaged characteristic element, following the general framework of continuum damage mechanics (CDM) and multiscale homogenization [7]. The homogenized element consists of two main components:

1. Damaged Layer P'P'P': Any arbitrary layer (0° , θ , or 90°) whose stiffness is reduced due to intralaminar damage modes such as transverse cracking, fiber breakage, or matrix microcracks.
2. Interface Layer: The interfacial region between adjacent plies that is susceptible to delamination. The interlayer damage is quantified using relative damage parameters derived from crack density and local strain conditions.

With these definitions, the damaged characteristic element (Figure 2-a) can be replaced by an equivalent homogenized element (Figure 2-b) with reduced orthotropic stiffness. This equivalence enables computational efficiency while preserving the essential physics of damage interaction between layers.

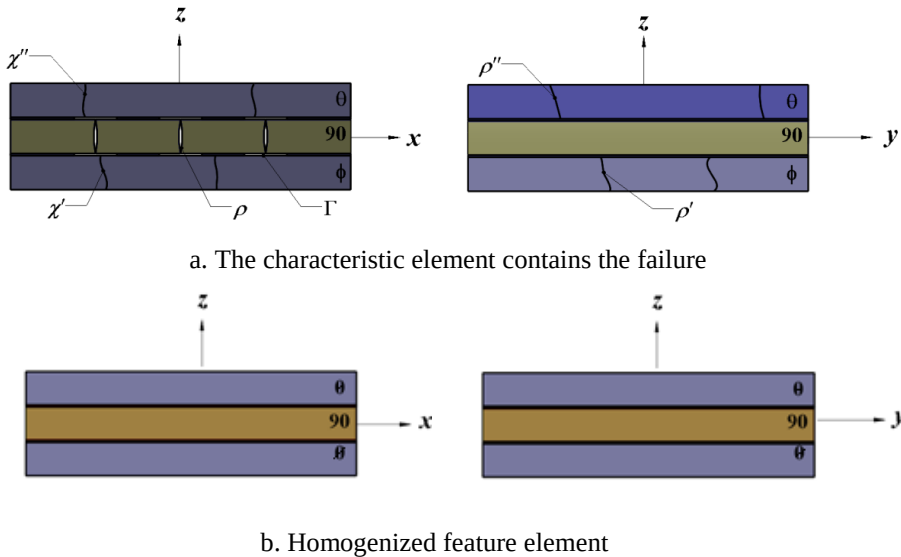


Figure 2. Example of a composite feature element (a) containing damage, (b) homogenized.

As a result, the equivalent stiffness matrix of the damaged layer P' can be expressed in another form.

$$S_{(\rho,x)}^{layer} = \begin{bmatrix} \frac{1}{E_1(1-d_F)} & -\frac{\nu_{12}}{E_1(1-d_F)} & 0 \\ -\frac{\nu_{21}(1-d_2)}{E_2(1-d_2)} & \frac{1}{E_2(1-d_2)} & 0 \\ 0 & 0 & \frac{1}{G_{12}(1-d_{12})} \end{bmatrix} \quad (1)$$

where:

- E_1 and E_2 are the Young's moduli of the layer along the principal material directions 1 (fiber direction) and 2 (transverse direction), respectively.
- G_{12} is the in-plane shear modulus of the layer.
- ν_{12} and ν_{21} are Poisson's ratios corresponding to the coupling between the 1 and 2 directions.
- d_F is the damage parameter related to fiber breakage.
- d_2 is the damage parameter associated with transverse matrix cracking.
- d_{12} represents the shear damage parameter due to the degradation of G_{12} .

The damage parameters are calculated based on crack density, local stress, and interlayer separation, following micromechanical formulations and experimental correlations [8]:

$$\begin{aligned} d_F &\approx \frac{\Delta E_1}{E_1} \\ d_2 &\approx \frac{\Delta E_2}{E_2} \\ d_{12} &= \frac{\Delta G_{12}}{G_{12}}. \end{aligned} \quad (1)$$

Similarly, the reduced interface stiffness matrix for modeling interlayer separation is formulated as a function of the relative damage parameters between adjacent layers:

$$S_{(\Delta)}^{Interface} = \begin{pmatrix} \frac{1}{E(1-d_{33})} & 0 & 0 \\ 0 & \frac{1}{G(1-d_{13})} & 0 \\ 0 & 0 & \frac{1}{G(1-d_{23})} \end{pmatrix} \quad (3)$$

Where, the parameters d_{33} , d_{13} and d_{23} are defined as follows:

$$\begin{aligned} d_{33} &\approx \frac{\Delta E}{E} \\ d_{13} &\approx d_{23} \approx \frac{\Delta G}{G} \end{aligned} \quad (4)$$

Where:

- E is the effective Young's modulus of the interface.
- G is the effective shear modulus of the interface.
- d_{33} represents the expected stiffness degradation of the interface due to opening-mode separation.
- d_{13} and d_{23} correspond to interfacial shear degradation along the two transverse directions.

This homogenization strategy enables mesoscale modeling of both intralaminar and interlaminar damage, capturing the interaction of matrix cracks, fiber breakage, and interlayer delamination without explicitly modeling every microcrack. Compared to classical cohesive zone models or virtual crack closure techniques, this approach reduces computational cost, avoids re-meshing, and requires fewer empirical parameters [9].

Furthermore, this framework is compatible with artificial intelligence (AI) and machine learning algorithms, which can predict damage evolution based on prior simulation or experimental data. Integrating AI improves the generalization of damage parameters under complex multiaxial loading conditions and accelerates the multiscale analysis [10].

In summary, the homogenized characteristic element serves as the foundation for the progressive damage model, allowing simultaneous

evaluation of matrix cracking, fiber breakage, and interlayer separation in laminated composites under general in-plane loading.

Determining the damage parameter for interlayer separation

A critical challenge in mesomechanical modeling of composite laminates is accurately defining damage evolution laws and the corresponding damage parameters for each failure mechanism under varying loading conditions. In particular, interlayer separation, which occurs at the interfaces between adjacent layers, plays a significant role in the progressive degradation of laminate stiffness and overall structural integrity [11]. The precise quantification of these parameters is essential for predicting the initiation and growth of delamination and for simulating the nonlinear behavior of composite laminates under complex stress fields.

In this study, the reduction in stiffness due to intralaminar cracks in adjacent layers and the resulting interface separation are analyzed using a mesoscale model under out-of-plane loading conditions. The approach is inspired by the experimental relationships proposed by Ladevèze et al. [12], which link the damage parameter to the crack density in the adjacent layers and the separation length at the interface. This relationship is formulated on the principle of energy equivalence between the micro- and mesoscales, providing a robust framework for capturing the interaction between matrix cracking and interlayer delamination.

In the present work, a hybrid micromechanics and artificial intelligence (AI) approach is employed to determine the resultant forces and damage parameters associated with matrix cracking in each ply $P'P'P'$ of the meso-model. The procedure involves the following steps:

1. **Material and Geometric Considerations:** An orthotropic multilayer composite is considered under a general in-plane and out-of-plane stress field. Each layer is characterized by its orthotropic mechanical properties, including the longitudinal Young's modulus E_1 , transverse Young's modulus E_2 in-plane shear modulus G_{12} , and Poisson's ratios ν_{12} and ν_{21} .
2. **Crack Density Analysis:** The crack density of layers adjacent to each interface is evaluated. Crack density, defined as the number of cracks per unit length in a ply, serves as a key indicator of damage accumulation. Layers with higher crack densities are more susceptible to interlayer delamination initiation.
3. **Interface Damage Detection using AI:** Artificial intelligence and machine learning tools are employed to detect incipient interlayer delamination.

Using prior simulation data or experimental measurements, the AI algorithm identifies regions where stress concentrations and crack densities are sufficient to trigger interface separation.

4. **Damage Parameter Calculation:** Once the susceptible regions are identified, the micromechanics-AI framework calculates the damage parameters according to the type of failure mechanism:
 - d_{21} and d_{12} represent stiffness degradation due to transverse matrix cracking.
 - d_F represents stiffness reduction due to fiber breakage.
 - d_{33} , d_{13} , and d_{23} characterize the reduction in interface stiffness due to interlayer separation, including standard and shear modes.

The damage parameters are evaluated as functions of the background crack density, the failure mechanism, and the applied stress field, enabling the model to handle both a single cracked layer and a multilayer laminate containing multiple cracks. Additionally, the AI-based framework can predict stress and displacement fields under complex multiaxial loading conditions, ensuring an accurate representation of the mechanical response and the interaction between intralaminar and interlaminar damage [13].

In summary, this hybrid micromechanics-AI methodology enables precise quantification of interlayer damage parameters, facilitating the simulation of progressive delamination in composite laminates. By combining experimental correlations, micromechanical analysis, and machine-learning predictions, the model provides a robust, efficient, and generalizable approach for evaluating the evolution of interlayer separation under realistic loading conditions. This method significantly enhances the predictive capability of multiscale damage models while reducing dependence on extensive empirical testing.

Proposed continuum damage mechanics model

In the present study, an AI-based micromechanical model is developed to overcome the inherent limitations of traditional meso-scale models in predicting the progressive failure of composite laminates. Conventional mesomodels often struggle to accurately capture the interaction between intralaminar (matrix cracking and fiber breakage) and interlaminar (delamination) damage modes under complex loading conditions. To address these limitations, the proposed model extends micromechanical formulations for orthotropic layers, combined with the approach introduced by Zhang et al. [14], enabling the comprehensive analysis of matrix cracking, fiber breakage, and interlayer delamination.

The model is implemented as a custom subroutine within the ANSYS finite element environment using FORTRAN. This implementation leverages incremental growth techniques to analyze nonlinear material behavior and large deformations while maintaining compatibility with user-defined code interfaces, such as the Yosemite subroutine framework. By doing so, the model can simulate the evolution of damage within each layer and its interaction with the surrounding layers, providing an accurate prediction of the laminate's progressive failure.

Micromechanical Feature Elements and Gaussian Points

In this framework, each finite element in each layer is discretized, and the associated Gaussian points are treated as key feature points for damage evaluation. These Gaussian points serve as representative locations for monitoring the local material response, crack density, and stress state. A multilayer feature element is then defined at each Gaussian point, encompassing information from the current layer and its adjacent layers. This approach allows capturing the interdependency between layers, particularly the transfer of stress and initiation of interlayer delamination.

The dimensions of the feature element, including its length and practical volume, are dynamically updated based on the local crack density. Using either AI predictions or existing micromechanical models, the reduced stiffness of the damaged element is calculated according to the identified intralaminar damage mechanisms.

Modeling Interlayer Separation

To explicitly model interlayer separation, a special interface layer (common boundary) is defined between each pair of adjacent layers in the finite element mesh (illustrated in red in Figure 3). At this interface, the Gaussian points common to the upper and lower layers are identified and analyzed. Based on the local crack density of the surrounding layers and the applied load at the interface Gaussian points, the separation between layers is calculated using the AI-based predictive model. This enables the simultaneous evaluation of interlayer delamination alongside intralaminar damage.

The failure parameter associated with the interface is then computed, representing the local degree of separation and potential delamination growth. This procedure is repeated for all Gaussian points across all layers and for each incremental load step, ensuring a progressive and comprehensive assessment of damage evolution.

Progressive Damage Analysis and Convergence

After the local damage parameters and interlayer separations are determined, the residual forces for the entire multilayer structure are calculated. The model checks convergence criteria at each incremental step to ensure numerical stability and accuracy. If the criteria are not met, the load increment is adjusted, and calculations are repeated. This iterative procedure continues until the simulation reaches the desired load level or until global failure occurs. The overall workflow of the progressive damage analysis, including the interactions between intralaminar and interlaminar damage modes, is summarized in the flowchart presented in Figure 4.

By integrating AI predictions, micromechanical analysis, and finite element implementation, this continuum damage mechanics model provides a highly efficient, accurate, and generalizable framework for simulating the nonlinear behavior of composite laminates. The approach reduces reliance on empirical material parameters, enhances predictive capabilities under complex loading conditions, and allows for multiscale analysis of damage evolution in laminated composites.

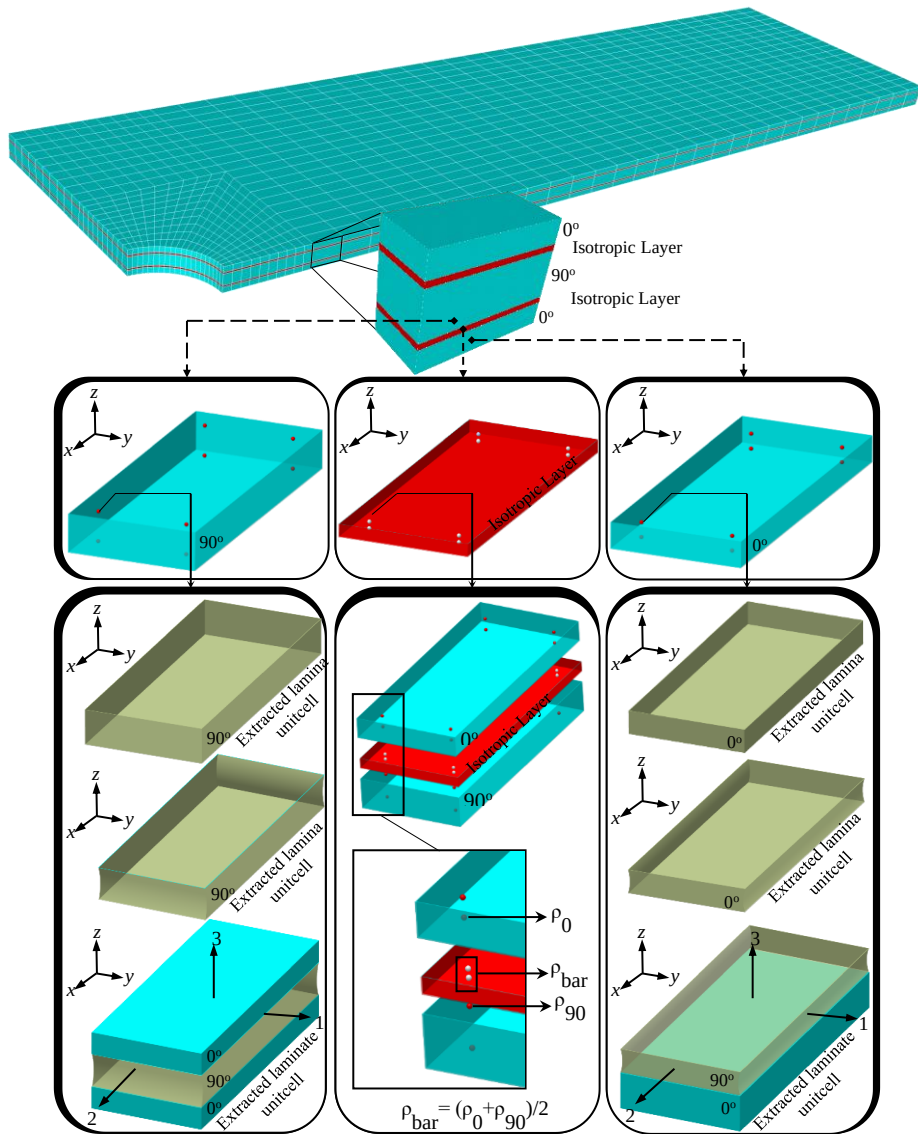


Figure 3. (a) Typical elementing of a composite multilayer (meso model), (b) magnification of the multilayer with a common boundary, (c) orthotropic layer, and (d) common boundary element.

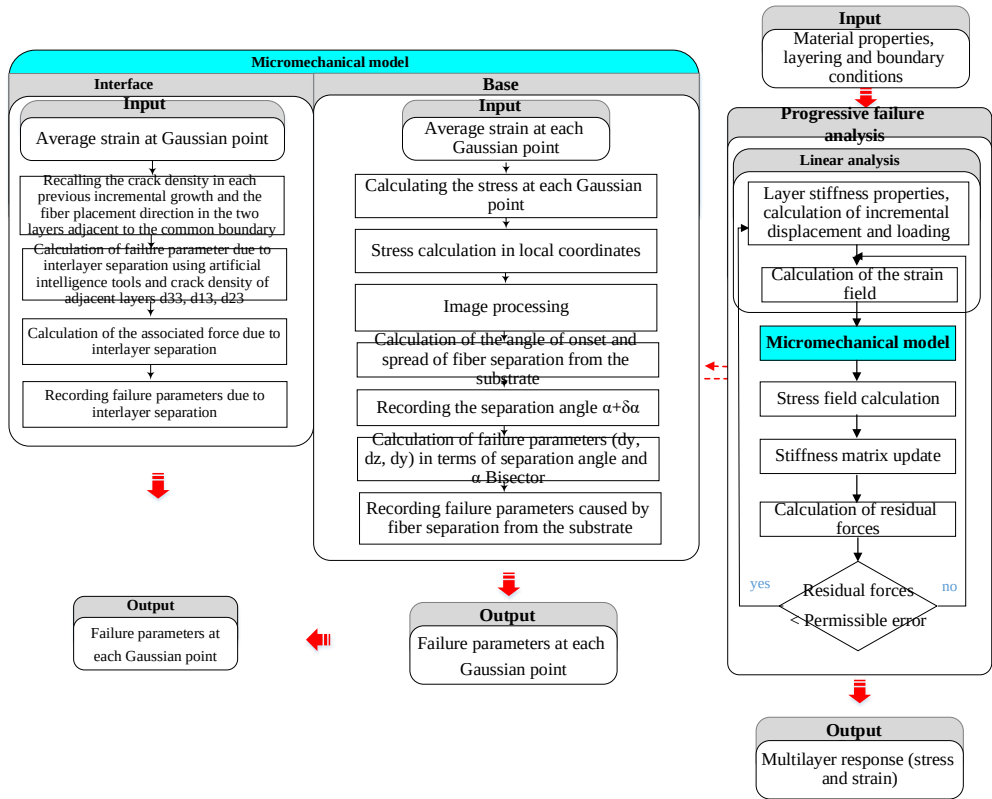


Figure 4. Flowchart for investigating the nonlinear behavior of a composite material containing failure mechanisms of matrix cracking, interlaminar separation, and fiber breakage.

Elements discretization in square cross-ply laminates

Accurate representation of interlaminar delamination and intralaminar damage in finite element simulations requires careful consideration of the element discretization along the laminate thickness. Inadequate mesh resolution can lead to significant errors in predicting out-of-plane stresses (δ_{zz} , δ_{yz} , and δ_{xz}) and, consequently, the initiation and propagation of interlayer separation. Therefore, determining the optimum number of elements is essential to ensure both accuracy and computational efficiency.

In this study, a square [0₂/90₄]_s cross-ply laminate with unit length was considered under uniaxial tensile displacement to investigate the effects of mesh discretization along the thickness direction (Figure 5). The laminate was discretized using four element counts per ply: $N = 1, 3, 4$, and 30. This procedure

allows assessment of the convergence of out-of-plane stress components both within the plies and at the interface layers.

The material properties assigned to the laminate are as follows:

- Longitudinal Young's modulus (E_1) = 139 GPa
- Transverse Young's modulus (E_2) = 10 GPa
- In-plane shear modulus (G_{12}) = 5.2 GPa
- Out-of-plane shear modulus (G_{23}) = 3.5 GPa
- Poisson's ratio ν_{12} = 0.32
- Poisson's ratio ν_{23} = 0.49
- Ply thickness = 0.203 mm

The variation of out-of-plane stresses along the laminate thickness for different mesh densities is shown in Figure 6 (a, b, and c), illustrating the distribution of σ_{zz} , σ_{yz} , and σ_{xz} , respectively. It is observed that the stress profiles for $N > 3$ are nearly identical, indicating that further refinement beyond 3 elements per ply does not significantly improve accuracy.

Based on these results, a mesh discretization of three elements per ply thickness was selected as the optimum choice. This selection balances computational efficiency and numerical accuracy, ensuring reliable prediction of both intralaminar damage and interlayer delamination while minimizing simulation time and computational resources.

Careful element discretization is particularly important when simulating progressive damage and interlayer separation in composite laminates. Accurate representation of stress gradients near interfaces and potential crack paths directly affects the reliability of predicted damage evolution and ultimate failure load. Using the optimized mesh, subsequent finite element simulations, including open-hole tension tests and crack density evolution studies, can be performed with confidence in their numerical fidelity. It is worth noting that the mesh convergence analysis of the open-hole laminate for matrix cracking analysis has been reported in Ref. [15].

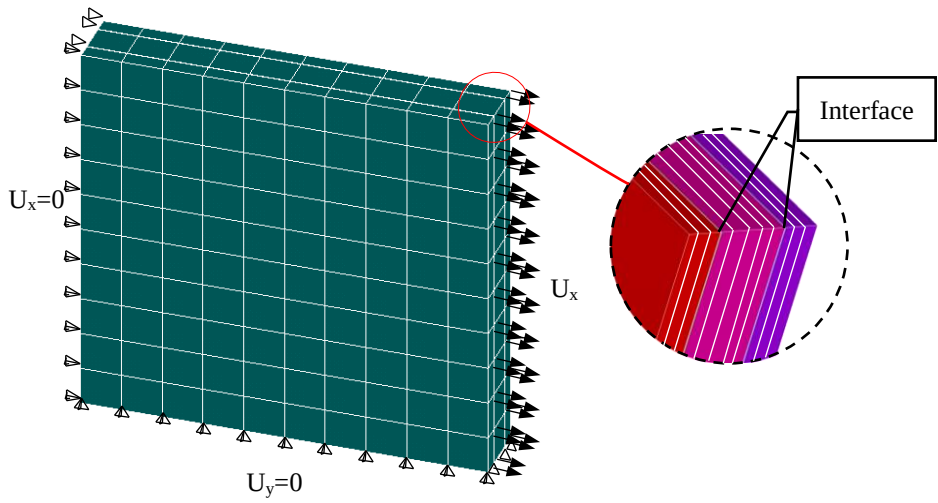


Fig. 5. Representation of the unit square model with loading and boundary conditions

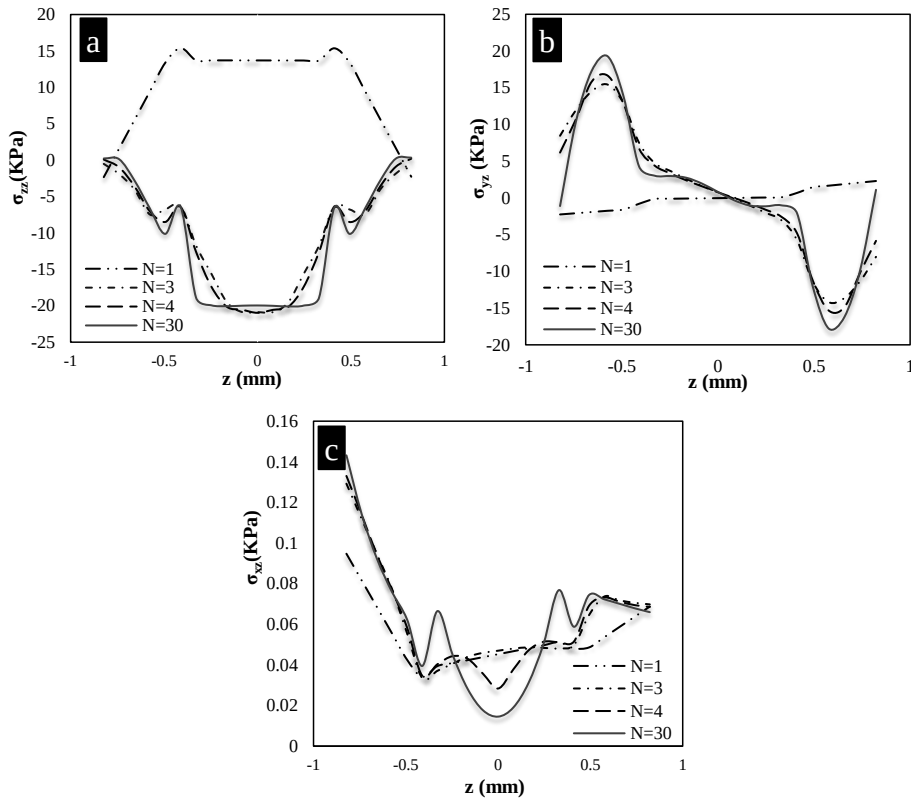


Fig. 6. Variation of laminate out-of-plane stress in thickness direction for a $[0_2/90_4]_s$ laminate: (a) σ_{zz} , (b) σ_{yz} , and (c) σ_{xz} .

In this section, the results of the progressive damage model are presented for open-hole tensile tests and compared with available experimental data. The primary aim is to validate the proposed finite element model and demonstrate its ability to accurately predict matrix cracking, fiber breakage, and interlayer delamination in cross-ply laminates containing a central hole.

A symmetric open-hole tensile specimen with a cross-ply laminate configuration was considered, as illustrated in Figure 7. The boundary conditions and the 3D finite element mesh of the specimen are shown in this figure. To accurately capture stress distribution and damage evolution, an eight-node brick element was used in all simulations. A total of 7200 elements were used for each ply and 2400 elements for each interface layer, ensuring sufficient resolution to model crack initiation and propagation as well as interlayer separation.

Due to the symmetry of the specimen, the analysis was performed on only one-quarter of the geometry, reducing computational effort while maintaining an accurate representation of the stress field and damage progression. Prescribed displacement boundary conditions were applied to simulate uniaxial tensile loading along the longitudinal direction of the laminate.

The adopted mesh density and element type were chosen based on the previous mesh sensitivity study (see previous section), which confirmed that three elements per ply thickness are sufficient to accurately capture both in-plane and out-of-plane stress components, as well as stress gradients at the interface. This level of discretization ensures that the model can reliably predict the chronology of damage evolution, including the initiation of transverse cracks in the 90-degree plies, subsequent splitting in the 0-degree plies, growth of interlayer delamination, and eventual fiber breakage.

By using this modeling strategy, the proposed progressive damage model provides a comprehensive representation of the mechanical behavior of laminates with geometric discontinuities, such as central holes. The high-resolution 3D mesh enables the capture of localized stress concentrations and accurately reflects the interactions between matrix cracking and interlayer delamination, which are critical for predicting the ultimate failure load of composite laminates under tensile loading.

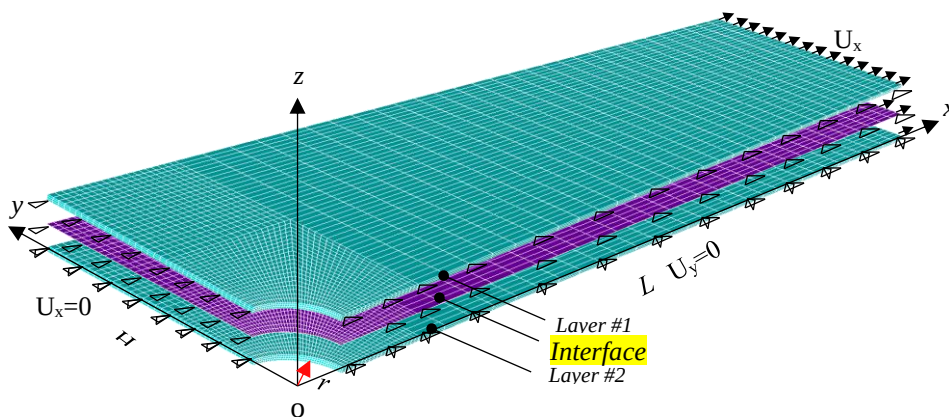


Fig. 7. Discretization of the open hole cross-ply laminate with loading and boundary conditions.

The stress-strain response of a [90₂/0₂]_s carbon fiber-reinforced polymer (CFRP) laminate was simulated using the developed progressive damage model and compared with the experimental results reported in [16], as shown in Figure 8. This comparison validates the predictive capability of the

proposed model for capturing the initiation and evolution of various damage mechanisms in cross-ply laminates with a central hole.

The material properties assigned to the laminate plies are as follows:

- Longitudinal Young's modulus (E_1) = 139.9 GPa
- Transverse Young's modulus (E_2) = 10 GPa
- In-plane shear modulus (G_{12}) = 5.2 GPa
- Out-of-plane shear modulus (G_{23}) = 3.5 GPa
- Poisson's ratio ν_{12} = 0.32
- Poisson's ratio ν_{23} = 0.49
- Critical energy release rate for delamination (G_c) = 450 J/m²
- Ply thickness = 0.203 mm
- Laminate length (L) = 150 mm
- Laminate width (H) = 36 mm
- Radius of central hole (R) = 3 mm

The interface properties between adjacent plies were set as follows:

- Young's modulus (E) = 2.4 GPa
- Poisson's ratio (ν) = 0.33
- Initial stiffness of the interface (Y_0) = 5.6 N/m
- Critical traction of the interface (Y_c) = 2750 N/m
- Interface thickness = 0.01015 mm

The stress-strain curves were obtained by dividing the resultant force along the loading direction by the laminate cross-sectional area. The progressive damage model accurately predicted the chronology of damage evolution, starting from transverse cracking in the 90-degree plies, followed by splitting in the 0-degree plies, which consequently led to interlayer delamination. The final failure stage involved fiber breakage in the 0-degree plies when the fiber traction criterion was reached.

The minor differences observed between the simulation results and previously reported data in Ref. [16] can be attributed to induced delamination and delamination formation near the free edges, which were not considered in the earlier study. Overall, the proposed model demonstrates excellent agreement with experimental results, effectively capturing both the initiation and propagation of intralaminar and interlaminar damage in open-hole laminates under tensile loading.

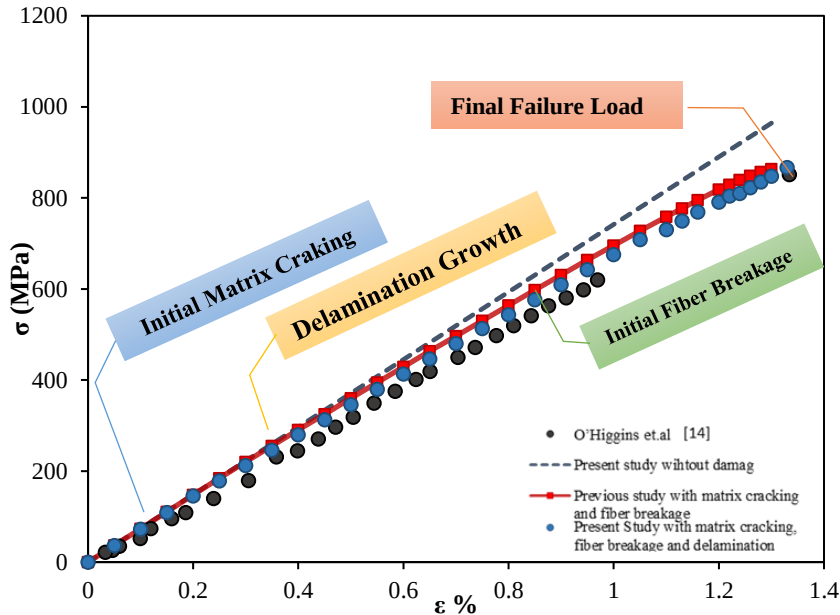


Fig. 8. The stress–strain response of $[90_2/0_2]_s$ CFRP laminate with open hole.

To further validate the proposed progressive damage model, the evolution of different damage types in a $[0_2/90_2]_s$ carbon/epoxy laminate containing a central hole under longitudinal tensile loading was investigated and compared with experimental results reported by Yashiro et al. [17]. The material properties of the laminate plies are as follows:

- Longitudinal Young's modulus (E_1) = 148 GPa
- Transverse Young's modulus (E_2) = 9.57 GPa
- In-plane shear modulus (G_{12}) = 3.5 GPa
- Out-of-plane shear modulus (G_{23}) = 4.5 GPa
- Poisson's ratio in-plane (ν_{12}) = 0.365
- Poisson's ratio out-of-plane (ν_{23}) = 0.49
- Critical energy release rate for delamination (G_c) = 250 J/m²
- Ply thickness = 0.25 mm
- Laminate length (L) = 80 mm
- Laminate width (H) = 25.6 mm
- Radius of central hole (R) = 2.5 mm

The interface properties were assigned as:

- Young's modulus (E) = 2.4 GPa

- Poisson's ratio (ν) = 0.33
- Initial interface stiffness (Y_0) = 5.6 N/m
- Critical traction of interface (Y_c) = 2750 N/m
- Interface thickness = 0.0125 mm

The simulation results, shown in Figures 9, 10, and 11, indicate that four distinct types of damage mechanisms occur simultaneously during tensile loading:

1. Transverse cracking in the 90-degree plies
2. Splitting in the 0-degree plies
3. Fiber breakage in the 0-degree plies
4. Interlayer delamination at the interface

The model accurately captured the chronology of damage evolution, from initiation to propagation and final rupture. Initially, transverse cracking occurs in the 90-degree plies, similar to the behavior observed in [90_2/0_2]_s laminates. However, the strain at which the first crack appears varies depending on the number and position of adjacent 90-degree plies. Once the first transverse crack forms, splitting in the 0-degree plies follows as the applied tension increases. This process establishes a continuous relationship between the crack density (number of cracks per unit length of laminate) and the applied tensile strain.

Simultaneously, interlayer delamination develops at the interface between adjacent plies, while fiber breakage begins at the edge of the hole in the 0-degree plies. Notably, the 90-degree plies remain free of fiber breakage throughout the simulation. At a longitudinal strain of 0.58%, initial splitting, transverse cracking, and interface delamination are observed near the hole edge (Figure 9). As the strain increases, splitting extends along the fiber direction, promoting further delamination growth, and the crack density increases progressively with applied strain, as illustrated in Figure 10.

The results demonstrate that the proposed model successfully captures the complex interactions between intralaminar and interlaminar damage mechanisms in cross-ply laminates with stress concentrators, providing accurate predictions of progressive failure behavior and the spatial evolution of damage under tensile loading conditions.

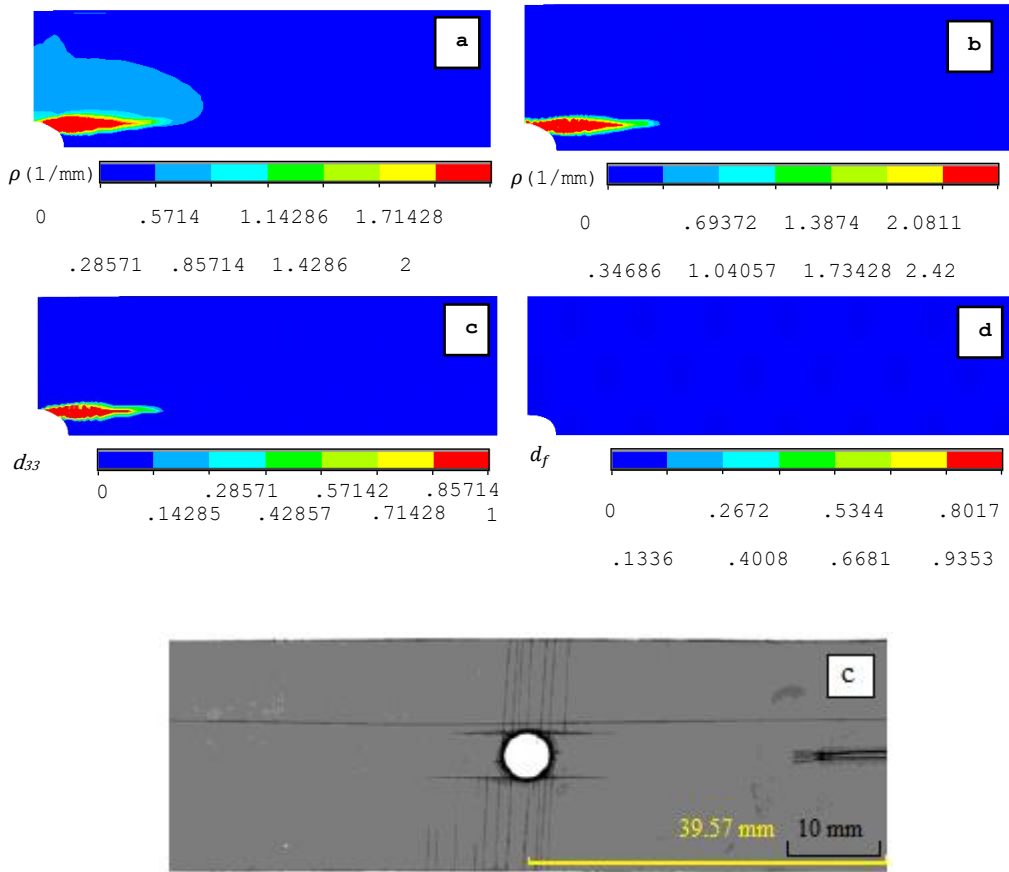


Fig. 9. Contour plot of damage events in $[0_2/90_2]_s$ CFRP under longitudinal deformation of 0.58%: (a) transverse cracking in 90° , (b) splitting in 0° , (c) delamination in the interface, (d) fiber breakage, and (e) Yashiro et al.[18].

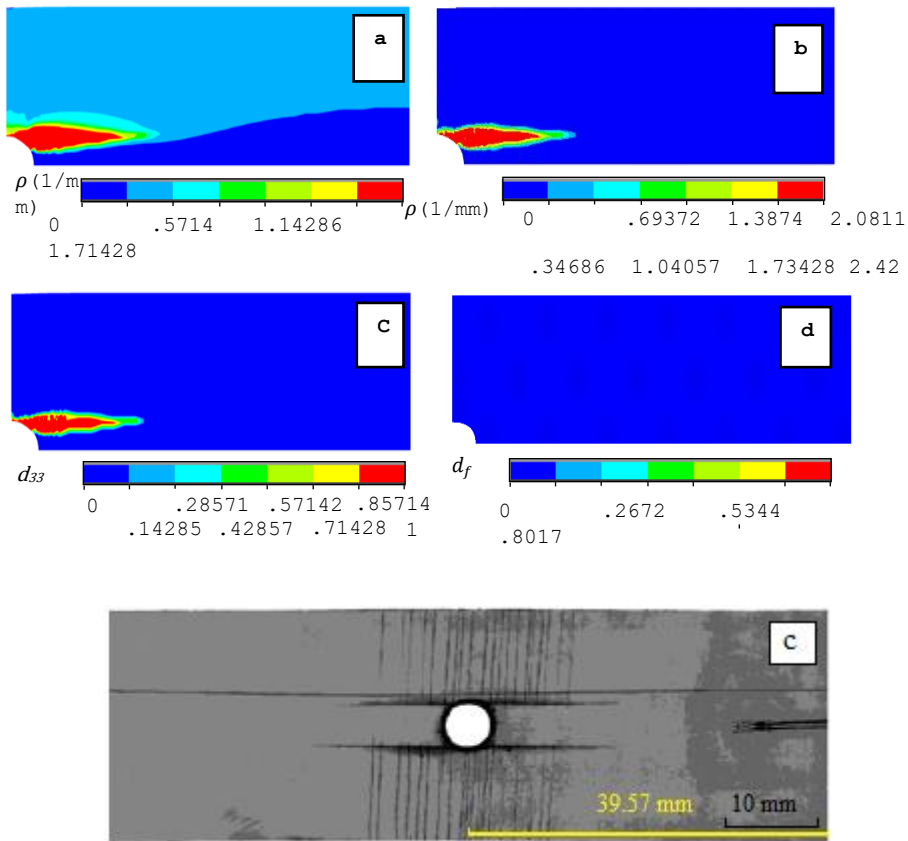


Fig.10. Contour plot of damage events in $[0_2/90_2]_s$ CFRP under longitudinal deformation of 0.77%: (a) transverse cracking 90°, (b) splitting 0°, (c) delamination in the interface, (d) fiber breakage, and (e) Yashiro et al. [18].

Finally, fiber rupture in the 0-degree plies propagates along the splitting paths. It reaches the laminate edges at a longitudinal strain of 1.07%, as illustrated in Figure 11—the comparison between the simulation results and X-ray experimental observations reported by Mofidian et al. [1] demonstrates the high predictive capability of the developed progressive damage model for capturing the sequence and interactions among multiple damage mechanisms. These mechanisms include:

- Splitting growth in the 0-degree plies
- Transverse cracking in the 90-degree plies
- Delamination propagation at the interface
- Fiber breakage in the 0-degree plies

The model accurately captures these damage modes simultaneously, reflecting realistic failure behavior under tensile loading conditions.

In general, the comparison of the predicted progressive damage results from the developed computational constitutive model with various experimental datasets shows good agreement. Specifically, the overall stress-strain response of the [90_2/0_2]_s CFRP laminate with an open hole, predicted by the proposed model, closely aligns with experimental results, confirming the reliability of the approach.

A significant advantage of the developed methodology is its ability to reduce the number of empirical material parameters needed to define the damage evolution laws. Traditionally, such parameters must be determined from both standard and non-standard experimental tests, which can be time-consuming and resource-intensive. By integrating micromechanical modeling, artificial intelligence, and machine learning, the present approach effectively estimates material response and damage parameters, providing an efficient and accurate tool for predicting the progressive failure of composite laminates.

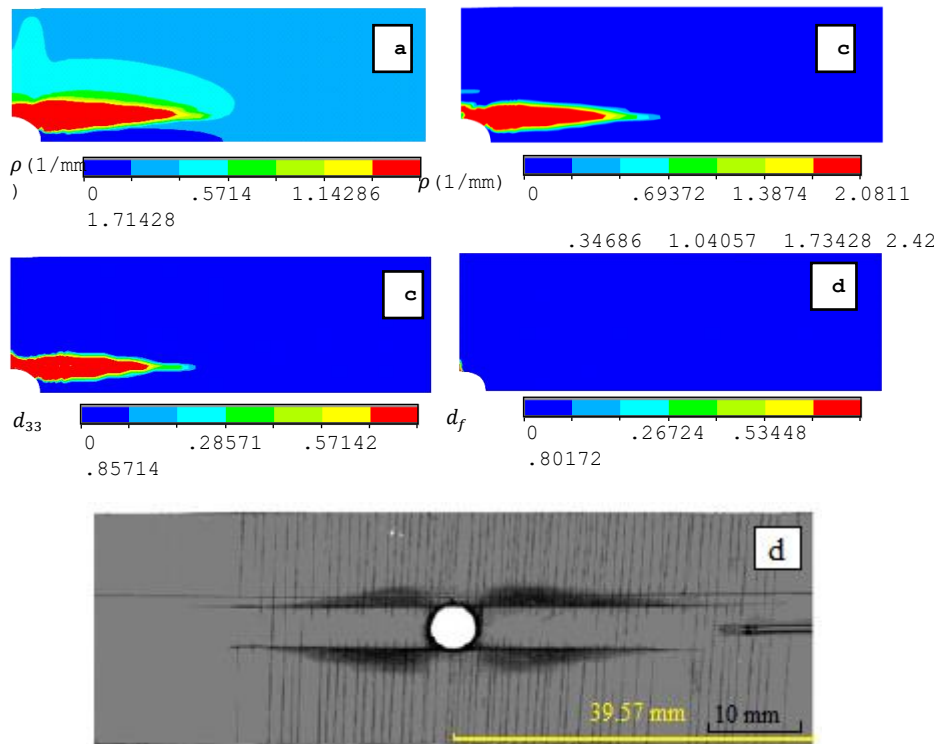


Fig. 11. Contour plot of damage events in $[0_2/90_2]_s$ CFRP under longitudinal deformation of 1.07%: (a) transverse cracking in 90° , (b) interface delamination, (c) splitting in 0° , (d) fiber breakage in 0° , (e) Yashiro et al.[18].

Conclusion

In this study, a novel artificial intelligence-based continuum damage mechanics model was developed to investigate the progressive failure behavior of cross-ply composite laminates, integrating micromechanical modeling, multiscale quasi-simultaneous analysis, and machine learning techniques to capture the complex interactions between matrix cracking, fiber breakage, and interlayer delamination. The model accurately predicts stress-strain responses, damage initiation, and propagation sequences under in-plane loading, with validation against open-hole tensile test data demonstrating its capability to reproduce transverse cracking in 90-degree plies, splitting and fiber rupture in 0-degree plies, and delamination growth at interfaces. By reducing reliance on empirical parameters, the proposed approach estimates damage parameters directly from computational and AI-based predictions, enhancing both predictive capability and efficiency. Key advantages include simultaneous modeling of intra- and interlayer damage mechanisms, flexibility to accommodate various materials and loading conditions, and reduced computational cost through optimized mesh discretization and the homogenization of characteristic elements. Overall, this framework provides a robust tool for structural analysis, material design, and optimization in composite engineering, with potential for future enhancements to incorporate complex 3D delamination patterns, environmental effects, and dynamic loading scenarios to broaden its applicability to real-world composite structures.

In addition to speeding up the multiscale analysis of composite materials with failure mechanisms, the introduced framework is highly flexible. It can adapt to a variety of materials and failure mechanisms at lower scales. The model is designed to integrate with other trained machine learning models to predict the mechanical behavior of materials at different scales. The salient features of this model include improving the efficiency of failure mechanism analysis, predicting the growth of fiber separation from the matrix, and providing solutions for homogenizing and localizing material behavior with high accuracy while reducing computational requirements. The method is flexible and can be used under various loading conditions and different structures, especially when limited mechanical data are available.

The development perspective of this method includes investigating more complex mechanical behaviors, such as interactions between different failure mechanisms, and a more accurate simulation, which will require greater

computational power. This machine learning-based approach enables the expansion of multiscale analyses and structural optimization and can be applied across various fields of mechanical science and engineering.

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