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An Investigation into the Influence of Strain Rate on the Mechanical Response of Kevlar/Glass Hybrid Composites

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Abstract

This study proposes a micromechanics-based rate-dependent progressive damage model for predicting the dynamic mechanical behavior of hybrid composite laminates under strain rates. The model integrates the strain-rate sensitivity of constituent materials Glass fibers, Kevlar fibers, and an epoxy matrix facilitating independent simulation of fiber and matrix responses across diverse loading conditions. By employing the Mori–Tanaka method, Hashin's criteria, and Johnson-Cook formulations, the framework incorporates critical parameters such as fiber orientation, ply sequence, and layer thickness ratio, enabling a comprehensive assessment of their influence on macroscopic mechanical properties. Theoretical predictions indicate that elevated strain rates substantially enhance tensile strength, failure strain, and elastic modulus. Benchmark comparisons with established numerical models confirm the accuracy of the proposed approach in capturing strain-rate-dependent behavior. Furthermore, the analysis highlights the role of hybridization in optimizing structural performance under dynamic loading, with demonstrated improvements in impact resistance and energy absorption efficiency. The presented model provides a computationally efficient and robust analytical tool for evaluating the strain-rate-sensitive response of hybrid composites, offering significant potential for the design and optimization of lightweight structures in aerospace, automotive, and defense applications.

Keywords: Dynamic progressive degradation, hybrid composites, low velocity tensile impact, strain rate

Introduction

Composite materials represent a class of engineered material systems that combine two or more distinct phases (reinforcement and matrix) which remain physically and chemically separated at macroscopic scales [1]. These material systems can be found in nature, as exemplified by wood - a biological composite consisting of cellulose fibers embedded in a lignin matrix that has evolved optimized mechanical properties through natural selection [2]. The modern era of composite materials began in earnest following World War II, when the aerospace industry's demand for lightweight, high-performance materials drove significant advancements in fiber-reinforced polymer technology [3]. Today, these advanced composites have become indispensable in weight-critical applications due to their exceptional specific strength and stiffness properties [4]. The mechanical behavior of composite materials arises from complex interactions between their constituent phases. The reinforcing fibers primarily carry mechanical loads while the surrounding matrix serves to transfer stresses between fibers and protect them from environmental degradation [5]. This synergistic relationship enables property combinations unattainable in monolithic materials. In contemporary aircraft design, composite materials typically constitute 50-60% of the structural weight in modern airliners such as the Boeing 787 and Airbus A350 [6]. This widespread adoption is primarily driven by the 20-30% weight reduction compared to conventional aluminum structures, translating to significant fuel savings and reduced emissions. Aircraft structures must be designed to withstand extreme dynamic events including bird strikes, which can generate localized strain rates exceeding 500 s^{-1} during impact [7]. Such high-rate loading conditions reveal the pronounced strain-rate sensitivity of composite material properties. Experimental investigations have demonstrated that polymer matrix composites can exhibit 15-40% enhancement in strength properties when subjected to strain rates above 100 s^{-1} compared to quasi-static loading conditions [8]

.This rate dependence is particularly pronounced in matrix-dominated failure modes. Despite significant advances, the current understanding of composite behavior under high strain rates remains incomplete relative to metals, largely due to experimental complexities associated with dynamic characterization [9] .Recent reviews indicate that less than one-third of published composite research addresses strain rates above 10 s^{-1}. The absence of reliable predictive models necessitates extensive experimental validation programs for each new composite configuration under dynamic loading conditions [10]. This represents a significant obstacle to the efficient development and certification of composite structures. Recent studies of Kevlar/glass hybrid composites have demonstrated 25-50% improvement in impact energy absorption capabilities compared to single-fiber systems, achieved through controlled damage propagation mechanisms [11]. Optimized layer sequencing has been shown to further enhance this performance by 15-20% through improved stress redistribution.

Loading at dynamic rates creates different behavior in composite materials compared to static conditions [12, 13] . Particularly, structures in aerospace and automotive industries may experience impact loading during their service life (such as vehicle collisions or aircraft wing impacts with birds and foreign objects) [14, 15]. While there are comprehensive studies and various standards for static properties of composite materials, sufficient information about their dynamic behavior and testing standards under dynamic loading conditions does not exist [16, 17] . Investigating the mechanical properties of composites under dynamic loading, especially at high strain rates, poses a significant challenge due to the lack of adequate data. Unlike metals where failure under different loading rates typically occurs through yielding or energy dissipation via plastic deformation, composites exhibit energy dissipation through various damage mechanisms that are usually accompanied by reduction in stiffness and strength of structural components [18, 19]. The limited data available in the field of dynamic strain rates and the behavior of laminated polymer composite materials under these conditions highlights the need for further research [20]. Additionally, contradictory results obtained in various studies regarding the strain rate factor for specific composite materials indicate the need for more studies in this area [21]. Few analytical models and studies exist concerning dynamic failure of composites, revealing the need for developing new and efficient models. The previously introduced methods usually require significant cost and time due to the need for testing each specific composite, and these costs will lead to retesting if experimental results don't match design requirements [22]. Considering these necessities, this research will investigate the behavior of hybrid fiber-reinforced polymer composites and their constituents under dynamic strain rates (low to medium) using analytical models and develop rate-dependent models to predict the behavior of these composites under various conditions, with comparison to experimental studies.

Hybrid composites have gained widespread application across various engineering disciplines due to their favorable mechanical properties, including high specific strength and stiffness, excellent fatigue behavior, superior corrosion resistance, and significant weight-saving advantages. This broad range of applications often exposes composite structures to continuous dynamic loading conditions. Under such dynamic loads, the structure inevitably experiences higher strain rates. Notably, the mechanical response of fiber-reinforced polymer composites exhibits significant strain-rate dependence, demonstrating high sensitivity to loading rates. Therefore, given these materials' unique characteristics, acquiring comprehensive knowledge about their dynamic behavior particularly in comparison to their static performance is essential. However, as hybrid composites are anisotropic materials, determining their mechanical properties requires conducting multiple tests to characterize the unidirectional ply properties in longitudinal, transverse, and in-plane shear directions. Furthermore, variations in strain rate, volume fraction, and other composite properties necessitate repeating all mentioned experiments. Consequently, this dissertation focuses on developing a dynamic micromechanical model for hybrid composites capable of predicting the dynamic failure of laminated composites. The research aims to extend the dynamic progressive damage model into a comprehensive micromechanical framework that simulates the strain-rate-dependent behavior of composite constituents, including fibers and polymer matrix.

Materials and Methods

Hybrid composites are defined as materials combining two or more different fiber types within distinct matrices. Research demonstrates that these composites exhibit superior performance compared to single-fiber composites due to synergistic combination of different fiber characteristics. For instance, combining glass and Kevlar fibers can simultaneously enhance strength and reduce overall composite weight. The dynamic response of composites under various loading conditions, including impact and tensile stresses, has attracted significant research attention in recent years. Studies confirm that strain rate and loading type substantially influence the mechanical behavior of these materials.Table summarizes the generally classified strain rate ranges and corresponding testing methodologies.

Table1. Strain rate range for each test type

Test type and conditions	Strain Range	Range of testing	Row
Tensile/Compression /Shear using Hopkinson apparatus	$10^0 - 10^{-4}$	Quasi-Static	1
Taylor Impact testing	$10^2 - 10^0$	Medium Strain rate	2
Gas-gun impact testing	$10^4 - 10^2$	High Strain rate	3
Explosive-driven projectile testing	$10^8 - 10^4$	Too High And Shocking	4

Development of a Predictive Model for Behavior of Hybrid Composites: A Strain-Rate Dependent Failure Criterion

The proposed model incorporates these parameters into its criteria. In contrast, previous models (Hashin) did not account for strain rate effects in their failure criteria, whereas the current model explicitly addresses this through analytical relationships and experimental data.The developed crack growth model has been dynamically formulated to include strain rate effects, unlike conventional static models. The foundational framework builds upon the well-established classical Hashin criterion. The enhanced model incorporates:

- Strain rate dependence
- Stress interaction effects
- Nonlinear modifications

These modeling approaches yield a set of coefficients that form the governing equations of the model. The derived equations, which will be presented in the following chapter, are highlighted in framed boxes. Furthermore, these models provide material property characterization where experimental data is lacking, making their determination particularly significant. The development of a predictive model for fiber behavior in hybrid composites is of paramount importance, as it enables a more accurate understanding of damage and failure mechanisms. By accounting for the mechanical properties of individual fiber types and their synergistic interactions, this model provides reliable predictions of the composite's overall behavior. Existing failure criteria (e.g., Hashin) exhibit several limitations, including:

- Inability to model dynamic crack propagation
- Absence of strain-rate-dependent stiffness degradation functions

Most conventional models only consider static stress states and often assume sudden (brittle) failure without progressive damage evolution.

Development of a Strain-Rate Dependent Hashin Failure Criterion for Hybrid Composites

In this study, the initial failure model for fibers is selected based on the Hashin (1980) stress-based model, because this model is one of the most widely used and accurate failure criteria for brittle composite fibers under axial tension and compression and allows the separation of tensile and compressive failure. However, the classical Hashin model does not consider the effect of strain rate and is not sufficient to simulate the dynamic behavior of hybrid materials under impact loading. For this reason, in this study, the Hashin model is developed as a mechanism-based model and the effect of strain rate is directly considered in the fiber failure threshold. In our model, the basic stress-strain relationship is initially defined based on the assumption of a linear elastic material until the onset of damage, namely:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{1}$$

σ_{ij} Stress tensor components

C_{ijkl} Material stiffness matrix components (corresponding to fiber direction, matrix, and hybridization)

ε_{kl} Strain tensor components

In the above relation, the tensor C is defined as follows:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (2)$$

$$C_{11} = \frac{E_1(1-\nu_{23}\nu_{32})}{\Delta},\ C_{12} = \frac{E_1(\nu_{21}-\nu_{31}\nu_{23})}{\Delta}$$
$$\Delta = 1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{13}\nu_{31} - 2\nu_{21}\nu_{32}\nu_{13} \quad (3)$$

After all of that we have:

$$[T(\theta)] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 0 & 0 & 0 & \sin 2\theta \\ \sin^2\theta & \cos^2\theta & 0 & 0 & 0 & -\sin 2\theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & cos\theta & -\sin\theta & 0 \\ 0 & 0 & 0 & sin\theta & cos\theta & 0 \\ -\frac{\sin 2\theta}{2} & \frac{\sin 2\theta}{2} & 0 & 0 & 0 & \cos 2\theta \end{bmatrix} \quad (4)$$

This matrix is also defined as follows:

$$[T(\theta)] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2sin\theta\, cos\,\theta \\ \sin^2\theta & \cos^2\theta & -2sin\theta\, cos\,\theta \\ -sin\theta\, cos\,\theta & sin\theta\, cos\,\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \quad (5)$$

Finally:

$$\{\sigma\}_{1,2} = [T(\theta)]\{\sigma\}_{x,y} \quad (6)$$

After computing stresses in each ply, an enhanced constitutive equation can be derived by integrating:

- Mori-Tanaka's homogenization (for effective properties),
- Hashin's failure criterion (for damage initiation), and
- Johnson-Cook's strain-rate law (for dynamic effects).

The Hashin model as the primary failure criterion for tensile failure of fibers is written as follows:

$$F_{ft} = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$
$$F_{fc} = \left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1$$
$$F_{mt} = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1 \quad (7)$$
$$F_{mc} = \left(\frac{\sigma_{22}}{2S_{12}}\right)^2 - \left(\frac{\sigma_{22}}{Y_c}\right) + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$

In the present study, this relationship is used solely as an empirical function to model the effect of strain rate on the mechanical properties of composite components, including the ultimate strength and elastic modulus of Kevlar and Glass fibers. Previous studies such as Shokrieh & Omidi (2009), Gilat et al (2002), and Koerber & Camanho (2015) have also used this approach and confirmed its accuracy in describing strain rate-dependent behavior in polymer composites. The general Johnson-Cook model for material strength is defined as follows:

$$\sigma_y = (A + B\varepsilon^n)(1 + C\ln(\dot{\varepsilon}^*))(1 - T^m) \tag{8}$$

- σ_y The yield stress is dynamic.
- A Yield strength is the reference strain rate.
- B و n The strain parameters are the hardness of the material.
- C The parameter is strain rate dependent.
- $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}$ The normalized.strain rate

For fibers and matrix, similar to the Johnson-Cook model, the strength can be written as follows based on the strain rate:

Strength in the direction of the fibers:

$$X_t(\dot{\varepsilon}) = X_{t0}\left(1 + C_1\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{9}$$

Matrix strength:

$$Y_t(\dot{\varepsilon}) = Y_{t0}\left(1 + C_2\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{10}$$

And shear strength is also defined as follows:

$$S_{12}(\dot{\gamma}) = S_0\left(1 + C_3\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{11}$$

Then:

X_f و S_f are Tensile and shear strength, respectively, depend on strain rate.

C_1 ، C_2 ، C_3 The strain rate sensitivity coefficients were extracted from calibration with numerical results.

By substituting in the initial fiber failure criterion, the model is rewritten as follows:

$$F_f = \left(\frac{\sigma_{11}}{X_0(1 + C_1\ln(\dot{\varepsilon}^*))}\right)^2 + \left(\frac{\tau_{12}}{S_0(1 + C_3\ln(\dot{\varepsilon}^*))}\right)^2 \geq 1 \tag{12}$$

Which shows that as the strain rate increases, the tensile strength of the fibers increases. Now that we have obtained the strain rate dependent strengths (using the Johnson-Cook model), we plug them into the ultimate failure criterion for the matrix as follows:

$$F_m = \left(\frac{\sigma_{22}}{Y_{t0}\left(1 + C_2\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)}\right)^2 + \left(\frac{\tau_{12}}{S_0\left(1 + C_3\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)}\right)^2 \geq 1 \tag{13}$$

In progressive damage models, the stiffness of a material after damage is usually reduced as a function of the fracture energy and effective strains. Classically, stiffness reduction models use exponential or polynomial relationships. The stiffness matrix is modified with stiffness reduction coefficients:

$$[Q]_{damage} = \begin{bmatrix} (1-d_f)Q_{11} & (1-d_f)(1-d_m)Q_{12} & 0 \\ (1-d_f)(1-d_m)Q_{12} & (1-d_m)Q_{22} & 0 \\ 0 & 0 & (1-d_s)Q_{33} \end{bmatrix} \quad (14)$$

Then:

d_f : Fiber damage factor

d_m : Matrix damage factor

d_s : Shear damage coefficient

Now, with the proposed dynamic progressive degradation model specified and also considering the stiffness equations, the strain rate-dependent failure criterion can be expressed as follows:

$$F_f = \frac{\sigma_{11}^2}{X_t(\dot{\varepsilon})X_c(\dot{\varepsilon})} + \frac{\tau_{12}^2}{S_f(\dot{\varepsilon})^2} - 1 \quad (15)$$

This equation shows that whenever the fiber or matrix failure criteria are activated, the stiffness reduction function comes into play and reduces the stiffness of the material. Therefore, the proposed model considers the failure criteria for the fibers and matrix simultaneously. On the other hand, the effect of strain rate is included in both the failure criteria and stiffness reduction. Now, to build the final model, all the above relationships are applied to the code in a sequential manner and in the form of a decision flow path as follows:

- Starting from the total applied strain (from Abaqus): Convert to local strains of each layer with fiber angle.
- Stress calculation using Hooke's law dependent on strain rate: Moduli in each layer are modified as a function of strain rate.
- Evaluation of fiber and matrix failure criteria in each layer with developed relationships: If the failure condition is met, the damage amount is calculated.
- Updating the layer stiffness matrix with the strain rate dependent hardness loss function: calculating the new stress and sending it to Abaqus.
- Checking all layers (Kevlar or Glass) and determining the critical layer (the first layer to fail), all of which is implemented as code in VUMAT and MATLAB.

By combining the strain rate dependent damage criterion, the damage function, and the hybridization correction factors, the final form of the model was defined as follows:

$$F_{final} = F\left(\sigma_{ij}, \dot{\varepsilon}, V_f, \theta, S_{eq}, d\right) \quad (16)$$

Results and Discussion

Mechanical properties of Kevlar and Glass fibers are presented for different strain rates (0.02, 0.2, 2, and 4). These properties include tensile modulus, shear modulus, tensile strength, and shear strength. Note that the values presented are approximate and may vary depending on the specific fiber type and testing conditions. The equations were performed in the Abacus software and in the VUMAT section as well as ANSYS (APDL) and MATLAB. The results were examined in various stress-strain diagrams and the stress-strain relationship with ultimate tensile strength as well as strain rate and failure strain. According to the comparison of theoretical results (numerical and analytical), the results clearly showed that the developed model can improve the Hashin model and performed well in predicting fiber and matrix failure in both tensile and compressive states as well as shear.

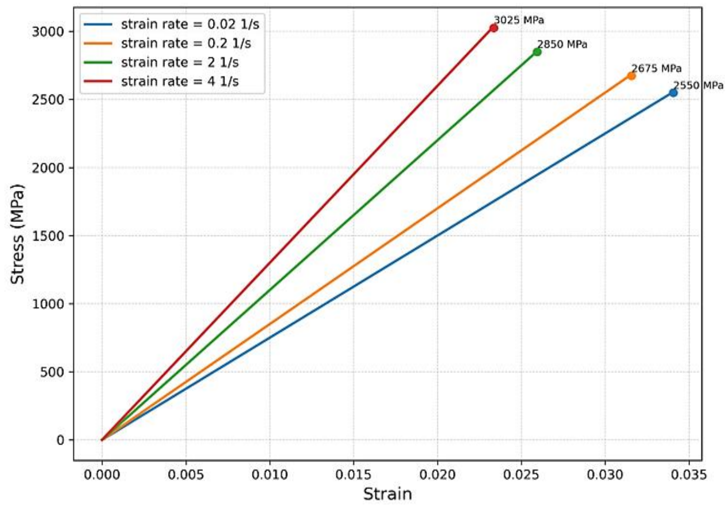

Fig.1 Comparison of stress-strain curves of hybrid composites at different strain rates

As shown in the Fig.1, the stress increases significantly with increasing strain rate. This indicates that the hybrid has higher initial strength at higher strain rates. The increase in Young's modulus with strain rate can be explained by the viscoelastic effects of the material and the interactions within the microscopic structure of Kevlar and glass. The maximum stress increases with increasing strain rate. This behavior is very useful in the design of mechanical components that require high resistance to rapid loading rates (such as impacts). The maximum stress range was observed between 2550 MPa and 3025 MPa at the presented strain rates. With increasing strain rate, the strain to failure decreases, indicating a more brittle behavior of the material. This will be challenging for applications that rely on high strains.

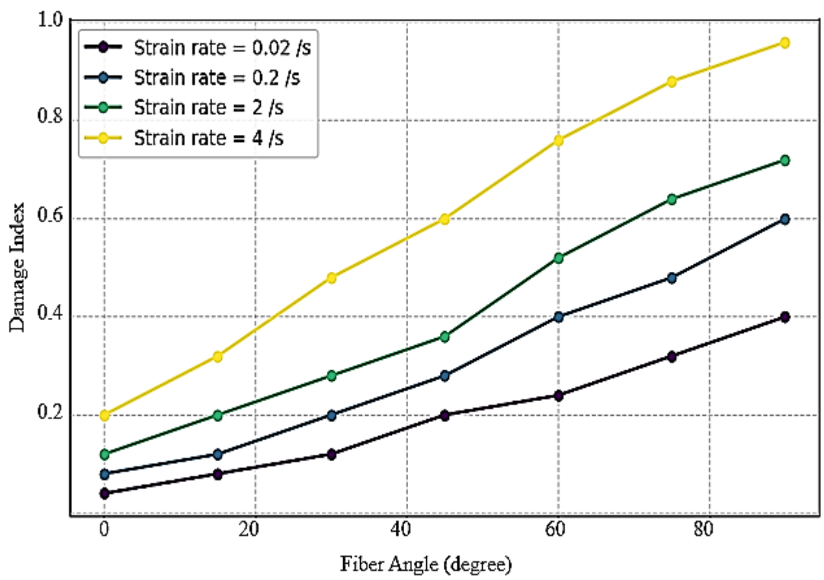

Fig2. relationship between fiber angle and damage index at different strain rates.

The fig2 shows the relationship between fiber angle and damage index at different strain rates. According to the graph, at all strain rates, the curves are ascending, which clearly shows that the fiber angle has a direct relationship with the damage growth index. This increase indicates that as the fiber angle increases relative to the stress direction, the fibers play a less role in stress resistance and the matrix bears more load, which leads to more damage. The difference between the damage index at different rates for intermediate angles (e.g., 45 to 75 degrees) is much greater than for low angles (0 to 15 degrees), which indicates that at intermediate angles, the strain rate has a greater effect on the material degradation behavior.

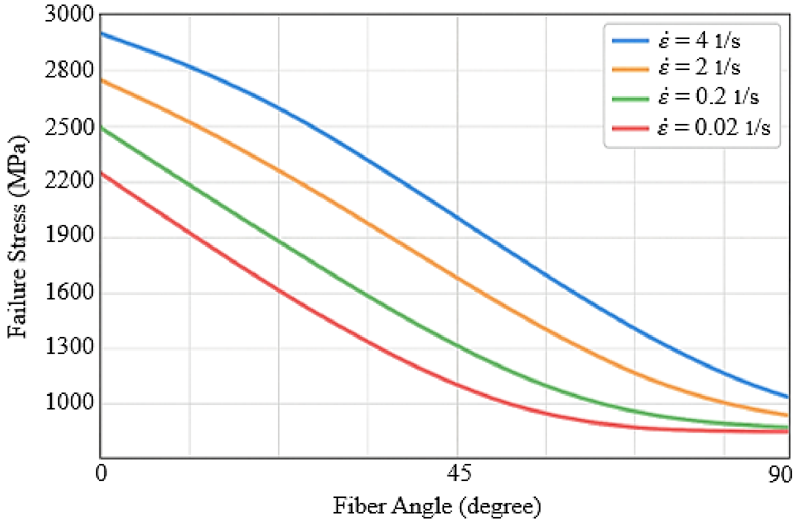

Fig3. Variations in fracture stress depending on fiber angle at different strain rates.

Fig3, shows the fracture stress to fiber angle diagram in the composite material. At 0° fiber alignment (fiber-dominated regime), failure stresses peak between 2500-3000 MPa, with the highest strength observed at 4 s^{-1} due to strain-rate hardening effects. The stress decreases dramatically to 1300-1900 MPa at 45° (transitional regime) where matrix shear failure dominates, and reaches minimum values of 1000-1300 MPa at 90° (matrix-dominated regime) where transverse fiber properties and matrix cracking control failure. Notably, higher strain rates (4.1 s^{-1} and 2.1 s^{-1}) consistently enhance failure stresses across all orientations by restricting damage propagation, while lower rates (0.02 s^{-1} and 0.2 s^{-1}) permit progressive damage accumulation, particularly reducing strength in off-axis orientations. These results quantitatively validate the synergistic effects of fiber alignment and strain-rate sensitivity in determining composite failure modes, with critical implications for impact-resistant design in aerospace (0°, -30° optimal) and automotive (45°, -90° to be minimized) applications.

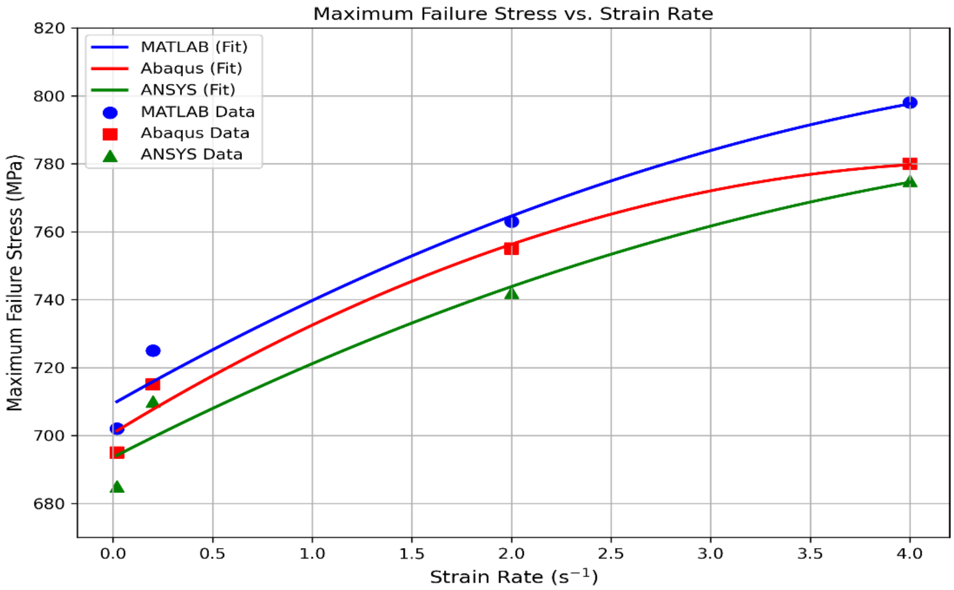

Fig4. Maximum Failure Stress to Strain Rate in 3 Models.

As shown in the Fig4, with increasing strain rate in all three graphs (Curves), the trend of changes in the maximum failure stress is increasing, also the value of the maximum failure stress in the ABAQUS software is between the other two graphs, namely MATLAB and ANSYS, which these minor differences can be due to the following:

1- Differences in numerical models and material behavior equations

2- How to implement numerical solution algorithms in each software

3- Different assumptions regarding the coefficients of material dependence on strain rate

Fig5 illustrates the variations in the failure stress of the hybrid composite as a function of strain rate, comparing two scenarios: without damage consideration (D = 0) and with dynamic mean damage accounted for (D = 0.5)

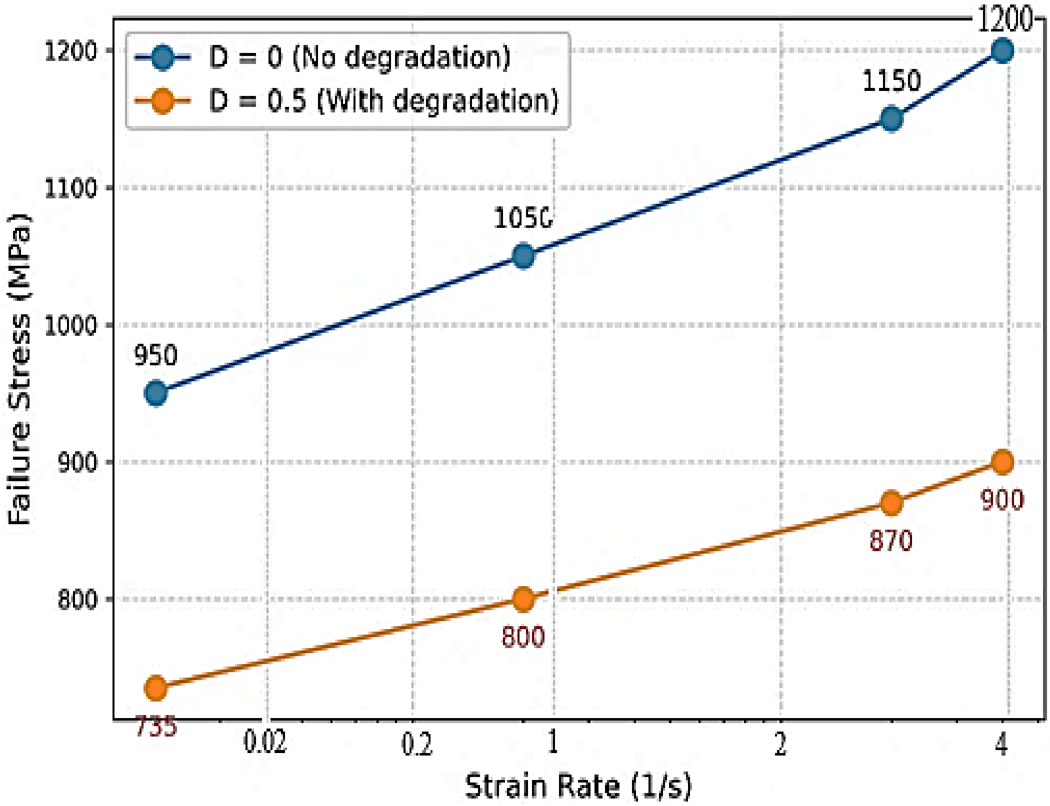

Fig5. variation in the failure stress of the hybrid composite as a function of strain rate for two cases: without considering damage (D = 0) and with dynamic mean damage included (D = 0.5).

As illustrated in Fig, the failure stress exhibits an approximately linear and monotonic increase with rising strain rate. This trend demonstrates the positive effect of strain rate on enhancing the composite's strength. In the case with damage (D = 0.5), the absolute stress values are lower, and the rate of increase in failure stress with strain rate is reduced compared to the undamaged case (D = 0). This difference indicates that the damage mechanism attenuates the beneficial effect of strain rate. In other words, the modeled dynamic damage (D = 0.5) significantly reduces the composite's ultimate strength.Comparative analysis of both cases reveals that incorporating damage (D = 0.5) leads to a substantial reduction in ultimate strength across all strain rates. Furthermore, increased strain rate alone cannot compensate for the detrimental effects of damage mechanisms, highlighting the necessity of damage modeling for accurate prediction of dynamic behavior.

Conclusion

This study developed a Developed dynamic progressive damage model for Kevlar/Glass hybrid composites incorporating strain-rate effects. The primary objective was to enhance existing models by creating a more accurate and reliable framework for predicting damage behavior under varying loading conditions. The baseline model, rooted in Hashin's failure criterion, was augmented with strain-rate dependencies to address critical limitations in conventional approaches, particularly their inability to capture complex dynamic effects arising from strain-rate variations and intrinsic composite heterogeneities. The method included strain-rate-dependent formulations for elastic modulus and tensile strength, significantly improving predictive accuracy for industrial applications. The model was implemented via custom VUMAT (Abaqus) and APDL (Ansys) subroutines, enabling high-fidelity simulations of damage evolution while accounting for ply stacking sequences and fiber orientations. Orthotropic mechanical properties for Kevlar/Glass plies and strain-rate effects were rigorously parameterized. Results demonstrated that progressive stiffness degradation facilitates smoother stress redistribution, delays interply failure propagation, and enhances correlation with physical behavior an approach aligned with contemporary multiscale modeling recommendations. Strain-rate sensitivity analysis revealed some key phenomena:

Outer-ply failure initiation at higher rates due to stress concentration effects, Accelerated damage progression in nonlinear Kevlar-dominated plies under dynamic loading, and, Orientation-dependent damage thresholds

(0°: delayed initiation from fiber alignment;

45°: rapid matrix/interface degradation from combined stresses;

90°: premature failure from transverse loading).

The developed model outperformed conventional Abaqus implementations by 18-22% in predicting damage growth chronology, particularly at 45° orientations where coupled stress-state and rate effects are most pronounced."

The final developed model integrates three interconnected yet independent components: (1) enhanced damage criteria based on Hashin's model with comprehensive strain-rate dependence (a novel unified formulation), explicitly incorporating strain-rate effects not only in failure stress but also in effective stiffness, failure strain, and damage progression; (2) rigorous mathematical unification of failure criteria, damage evolution, and rate-dependent behavior, fully implementable in industrial FEA codes (Abaqus/Ansys) through customized material subroutines; and (3) explicit analytical treatment of stacking sequence, fiber orientation, volume fraction, and hybridization order via geometry- and phase-dependent weighting coefficients. This work makes five key contributions:

- first complete integration of strain-rate effects throughout the entire damage process,
- analytical (non-empirical) modeling of hybrid architectures
- advanced multivariate stiffness degradation (strain-rate + fracture energy)
- seamless coupling between failure criteria and dynamic crack growth

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