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Effect of Strain Rate and Fiber Volume Fraction on the Mechanical Behavior of Kevlar/Glass Hybrid Composites

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Abstract

This research presents an advanced micromechanical framework for analyzing the effects of fiber volume fraction (V_f) and strain rate on the mechanical behavior of Kevlar/glass hybrid composites under strain rate. The proposed model captures rate-dependent failure mechanisms through the integration of Mori–Tanaka homogenization, a strain-rate-enhanced Hashin failure criterion, and constitutive formulations inspired by Johnson–Cook theory to simulate the evolution of stress, damage, and stiffness degradation across a wide range of loading rates. Emphasis is placed on the nonlinear coupling between V_f and strain rate ($\dot{\varepsilon}$), revealing that increases in V_f significantly enhance both ultimate tensile strength (UTS) and stiffness, especially at fiber-aligned orientations (0°), where load transfer efficiency is maximized. Nevertheless, elevated V_f and $\dot{\varepsilon}$ values correlate with a decline in failure strain, suggesting a transition toward more brittle failure modes. The model further identifies optimal V_f and strain rate configurations for maximizing energy absorption and maintaining structural integrity, offering critical insights for the design of impact-resistant hybrid composites. The consistency of the results within the theoretical framework (with deviations below 10%) supports the model's predictive capability and establishes a robust structure–property–rate relationship for dynamic loading applications.

Keywords: Hybrid composites, Kevlar/glass fibers, Strain rate sensitivity, Fiber volume fraction (V_f), Damage and stiffness degradation

Introduction

Hybrid fiber-reinforced polymer (FRP) composites have become indispensable in modern structural applications due to their exceptional combination of lightweight, high specific strength, and design flexibility. Among various hybrid configurations, Kevlar/glass composites stand out by offering a unique balance between toughness and stiffness, leveraging the ductility and energy absorption capacity of aramid fibers (Kevlar) and the high modulus and cost-effectiveness of glass fibers . [1, 2] This synergy allows for the design of composite materials with tailored performance characteristics for demanding applications in aerospace structures [3], automotive impact zones, [4] and defense systems such as ballistic armor [5]. One of the critical aspects influencing the mechanical performance of such hybrid composites is their strain-rate sensitivity. Fiber-reinforced composites, particularly those with polymer matrices, exhibit significant changes in mechanical behavior when subjected to dynamic or impact loading. Experimental studies have reported up to 40% increases in tensile strength and stiffness at elevated strain rates due to viscoelastic matrix effects, micro-inertial forces, and constrained damage propagation [6]. These strain-rate-dependent phenomena become especially critical in applications involving rapid deformation such as bird strikes on aircraft, crash events in vehicles, or ballistic impacts, where local strain rates can exceed 500 s^{-1} [7].

Despite the well-known rate sensitivity, current design models often fail to accurately predict composite response under dynamic conditions. Conventional failure theories such as Hashin [8]and Tsai-Wu [9] provide reliable estimates for static loading scenarios but lack mechanisms for capturing progressive damage or rate-dependent degradation of stiffness and strength. While rate-sensitive models like Johnson–Cook have been successfully applied to metals and polymers their extension to anisotropic and heterogeneous composite materials especially hybrid laminates remains insufficiently explored. Moreover, these models often do not incorporate microstructural variables such as fiber orientation and stacking sequence, both of which play a crucial role in defining stress distribution and failure modes [10, 11].Another pivotal factor affecting mechanical performance is the fiber volume fraction (V_f). Increasing V_f generally leads to higher tensile modulus and strength due to improved load transfer among fibers [12, 13]. However, excessive fiber content can result in decreased toughness and premature failure, especially under off-axis or matrix-dominated loading conditions [14]. Importantly, the interactive effects between V_f and strain rate (ε) are nonlinear and anisotropic, meaning that their influence depends strongly on fiber alignment, matrix ductility, and interfacial strength [15]. Despite this complexity, few studies have systematically investigated how varying V_f in hybrid composites affects rate-sensitive mechanical properties such as ultimate tensile strength (UTS), modulus, and failure strain [16]. Hybrid composites such as Kevlar/glass also introduce additional modeling challenges due to their multi-phase structure and anisotropic failure modes. Recent experimental efforts have demonstrated that optimized layer sequencing and volume fraction control can enhance damage tolerance by promoting gradual energy dissipation instead of sudden failure [17]. However, integrating these findings into predictive models requires coupling micro-mechanical formulations with dynamic failure criteria that reflect the evolving behavior of the composite under different loading conditions. In light of these challenges, the present study proposes a comprehensive micromechanical framework that unifies strain rate dependence and fiber volume fraction effects within a progressive damage modeling approach. Building upon the classical Hashin failure theory and enhanced with the Johnson–Cook strain-rate law the model incorporates stiffness degradation laws, homogenization techniques (Mori–Tanaka), and empirical formulations that capture anisotropic failure across varying fiber orientations and stacking sequences. By examining the coupled effects of V_f and strain rate on mechanical properties such as UTS, modulus, and damage evolution, this work addresses a key gap in hybrid composite modeling. The findings provide both theoretical insight and practical design guidance for engineering composite structures exposed to variable dynamic loads. Ultimately, this research aims to support the development of next-generation materials and simulation tools for high-performance, impact-resistant applications.

Materials and Methods

In this study, the mechanical behavior of Kevlar/glass hybrid composites under dynamic loading is modeled through a micromechanical framework that explicitly incorporates the effects of fiber volume fraction (V_f) and strain rate (ε) on key mechanical parameters including ultimate tensile strength (UTS), elastic modulus (E), and failure strain (ε_f). The formulation is based on a rate-dependent extension of the Hashin failure criterion, coupled with the Johnson–Cook law to capture strain-rate-sensitive behavior of both fiber and matrix constituents. A Mori–Tanaka homogenization scheme is applied to predict the effective stiffness tensor of each composite layer as a function of V_f, fiber orientation, and constituent moduli. the initial failure model for fibers is selected based on the Hashin 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:

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

After all of that we have:

$$[T(\theta)] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 0 & 0 & 0 & \sin 2\theta \\ \sin^2\theta & \cos^2\theta & 0 & 0 & 0 & -\sin 2\theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & cos\theta & -\sin\theta & 0 \\ 0 & 0 & 0 & sin\theta & cos\theta & 0 \\ -\frac{\sin 2\theta}{2} & \frac{\sin 2\theta}{2} & 0 & 0 & 0 & \cos 2\theta \end{bmatrix} \quad (3)$$

This matrix is also defined as follows:

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

Finally:

$$\{\sigma\}_{1,2} = [T(\theta)]\{\sigma\}_{x,y} \quad (5)$$

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).

Mori-Tanaka Method

In order to determine the strain rate-dependent orthotropic properties of the layers, a semi-analytical solution based on the Mori–Tanaka model is employed. The effective Young’s modulus in the fiber (longitudinal) direction (E_1) can also be expressed as Equation (6):

$$E_1(\dot{\varepsilon}) = E_f(\dot{\varepsilon})\emptyset + E_m(\dot{\varepsilon})(1 - \emptyset) \quad (6)$$

The effective transverse Young’s modulus (E_2) can also be obtained from Equation (7):

$$E_2(\dot{\varepsilon}) = \frac{E_m(\dot{\varepsilon})\left[1+\phi(\frac{E_f(\dot{\varepsilon})}{E_m(\dot{\varepsilon})}-1\right]}{1-\phi} \quad (7)$$

Similarly, the shear modulus G12 can be updated in the progressive damage and strain-rate-dependent regime using Equation (8), following the same approach as for the other properties:

$$G_{12}(\dot{\varepsilon}) = \frac{G_m(\dot{\varepsilon})\left[1+\phi(\frac{G_f(\dot{\varepsilon})}{G_m(\dot{\varepsilon})}-1\right]}{1-\phi} \tag{8}$$

To calculate Poisson's ratio, Equation (9) will be used:

$$\nu_{12}(\dot{\varepsilon}) = \nu_f(\dot{\varepsilon})\phi + \nu_m(\dot{\varepsilon})(1-\phi) \tag{9}$$

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

$$F_{ft} = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$

$$F_{fc} = \left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1$$

$$F_{mt} = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1 \tag{10}$$

$$F_{mc} = \left(\frac{\sigma_{22}}{2S_{12}}\right)^2 - \left(\frac{\sigma_{22}}{Y_c}\right) + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$

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:

$$\sigma_y = (A + B\varepsilon^n)(1 + C\ln(\dot{\varepsilon}^*))(1 - T^m) \tag{11}$$

- σ_y The yield stress is dynamic.
- A Yield strength is the reference strain rate.
- B , 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:

$$X_t(\dot{\varepsilon}) = X_{t0}\left(1 + C_1\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{12}$$

Matrix resistance:

$$Y_t(\dot{\varepsilon}) = Y_{t0}\left(1 + C_2\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{13}$$

And shear strength is also defined as follows:

$$S_{12}(\dot{\gamma}) = S_0\left(1 + C_3 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right) \tag{14}$$

Then:

X, Y, S 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:

$$F_f = \left(\frac{\sigma_{11}}{X_0(1 + C_1 \ln(\dot{\varepsilon}^*))}\right)^2 + \left(\frac{\tau_{12}}{S_0(1 + C_3 \ln(\dot{\varepsilon}^*))}\right)^2 \geq 1 \tag{15}$$

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:

$$F_m = \left(\frac{\sigma_{22}}{Y_{t0}\left(1 + C_2 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)}\right)^2 + \left(\frac{\tau_{12}}{S_0\left(1 + C_3 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)}\right)^2 \geq 1 \tag{16}$$

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:

$$[Q]_{damage} = \begin{bmatrix} (1-d_f)Q_{11} & (1-d_f)(1-d_m)Q_{12} & 0 \\ (1-d_f)(1-d_m)Q_{12} & (1-d_m)Q_{22} & 0 \\ 0 & 0 & (1-d_s)Q_{33} \end{bmatrix} \tag{17}$$

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:

$$F_f = \frac{\sigma_{11}^2}{X_t(\dot{\varepsilon})X_c(\dot{\varepsilon})} + \frac{\tau_{12}^2}{S_f(\dot{\varepsilon})^2} - 1 \tag{18}$$

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: 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)

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:

$$F_{final} = F(\sigma_{ij}, \dot{\varepsilon}, V_f, \theta, S_{eq}, d) \tag{19}$$

Results and Discussion

Influence of Strain Rate at Varying Volume Fractions

A consistent trend was observed wherein increasing the strain rate led to notable improvements in ultimate tensile strength. However, this enhancement was strongly affected by the fiber volume fraction. At lower V_f levels (e.g., 30%), the improvement in strength with increased strain rate was relatively moderate. In contrast, composites with higher fiber content (e.g., 70%) experienced a more pronounced increase in strength under the same strain rate increment. This implies that the reinforcing effect of strain rate is significantly amplified when the material is fiber-dominated, due to the load-bearing capacity and rate sensitivity of the fibrous phase. This behavior underscores the importance of considering V_f as a rate-dependent performance amplifier. At higher strain rates, the energy input is more efficiently absorbed and distributed by the stiffer fiber network, which delays matrix cracking and improves load transfer, particularly when fibers are aligned with the loading direction.

Correlation Between Volume Fraction and Elastic Modulus

An almost linear increase in elastic modulus was observed with increasing fiber volume fraction, which is consistent with the classic rule-of-mixtures prediction. The contribution of fibers becomes more dominant at higher V_f values, resulting in a stiffer composite structure. This trend was evident across all strain rates, although the magnitude of the modulus increase was somewhat more significant at lower V_f levels when the matrix phase was still mechanically influential. Under dynamic loading, a modest additional increase in modulus was observed due to strain-rate sensitivity of the matrix, especially in composites with lower fiber content.

Volume Fraction Effects on Failure Strain

In contrast to the positive influence of V_f on strength and stiffness, the failure strain exhibited a decreasing trend with increasing fiber content. This reduction in ductility is more pronounced at higher strain rates, indicating that a stiffer, fiber-dominated composite system is also more brittle under dynamic loading. In high-V_f composites, the material is less able to accommodate plastic deformation or progressive matrix cracking, leading to a more sudden failure once the damage initiates. This behavior suggests a trade-off between stiffness/strength and ductility/toughness that must be carefully considered in design.

Comparative Analysis of Multiple Parameters

A comparative analysis across different configurations reveals the following:

- At low V_f (30%), the mechanical behavior is matrix-dominated, with moderate strength gains from increased strain rate and relatively stable failure strain. This configuration is more ductile but mechanically less robust.
- At intermediate V_f (50%), a balanced response is achieved, offering a good combination of strength, stiffness, and damage tolerance. This configuration is suitable for applications requiring both energy absorption and load bearing under moderate dynamic loads.

- At high V_f (70%), the composite exhibits maximum tensile strength and modulus, especially under high strain rates. However, the failure strain is significantly reduced, resulting in a brittle failure profile. Such a configuration is ideal for impact-resistant but non-deformable applications where structural rigidity is prioritized.

Overall Interpretation and Design Implications

These findings confirm that fiber volume fraction is the primary structural variable controlling the mechanical performance of hybrid composites, while strain rate acts as a performance modifier that either amplifies or mitigates the inherent behavior based on the material's internal architecture. The interaction between these two variables defines the trade-off envelope between strength and ductility. For designers, the implication is clear: increasing V_f improves load-carrying capacity but reduces failure strain, and the extent of this trade-off becomes more severe at higher loading rates. Therefore, the choice of V_f must align with the application's expected loading conditions. For instance:

- High-V_f composites are suitable for aerospace skins and armor panels subjected to rapid impact,
- Medium-V_f systems are optimal for automotive crash zones where both strength and energy dissipation are required,
- Low-V_f composites may serve better in structures where ductility and damage tolerance are more critical than stiffness.
- This discussion lays the groundwork for advanced material optimization strategies by correlating microstructural design (V_f) with macroscale performance outcomes under dynamic conditions.

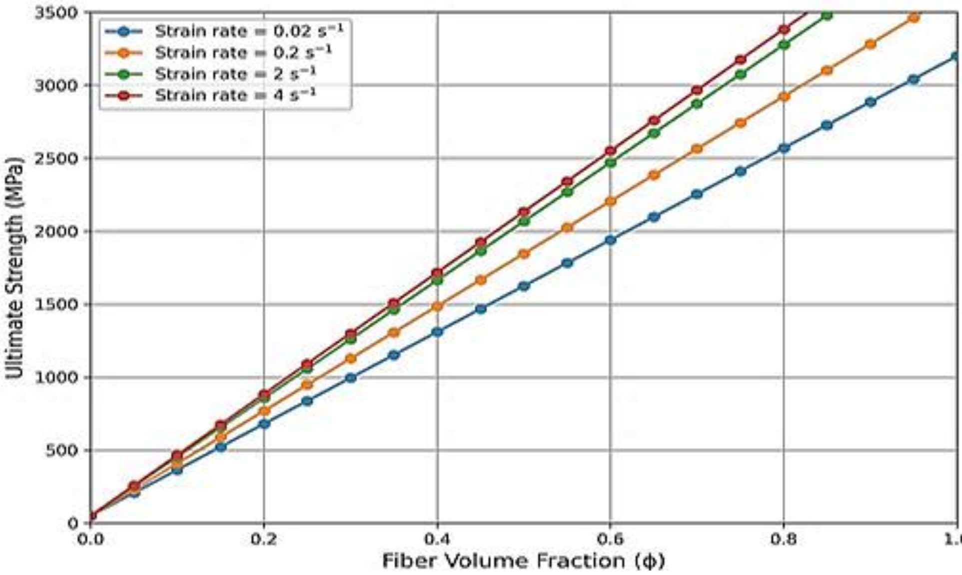

Fig 1 The effect of fiber volume fraction on ultimate strength at different strain rates

As illustrated in Fig 1, the composite exhibits matrix-dominated behavior at zero fiber volume fraction ($\phi = 0$), with ultimate stress equivalent to the matrix strength. Conversely, at unity fiber volume fraction ($\phi = 1$), the material demonstrates purely fiber-dependent behavior, where ultimate stress corresponds to fiber strength at the given strain rate. The results reveal a linear correlation between fiber content and mechanical performance, where increasing ϕ enhances the fiber contribution to composite strength, causing the material behavior to progressively approach that of the pure fiber. Notably, while fiber ultimate stress is relatively lower at quasi-static strain rates (0.02 s^{-1}), reaching 3200 MPa at $\phi = 1$, it shows significant strain-rate sensitivity - increasing to approximately 3450 MPa at 4 s^{-1}. This strain-rate dependent strengthening effect propagates through the composite system via the rule of mixtures, substantially influencing the overall stress-strain response.

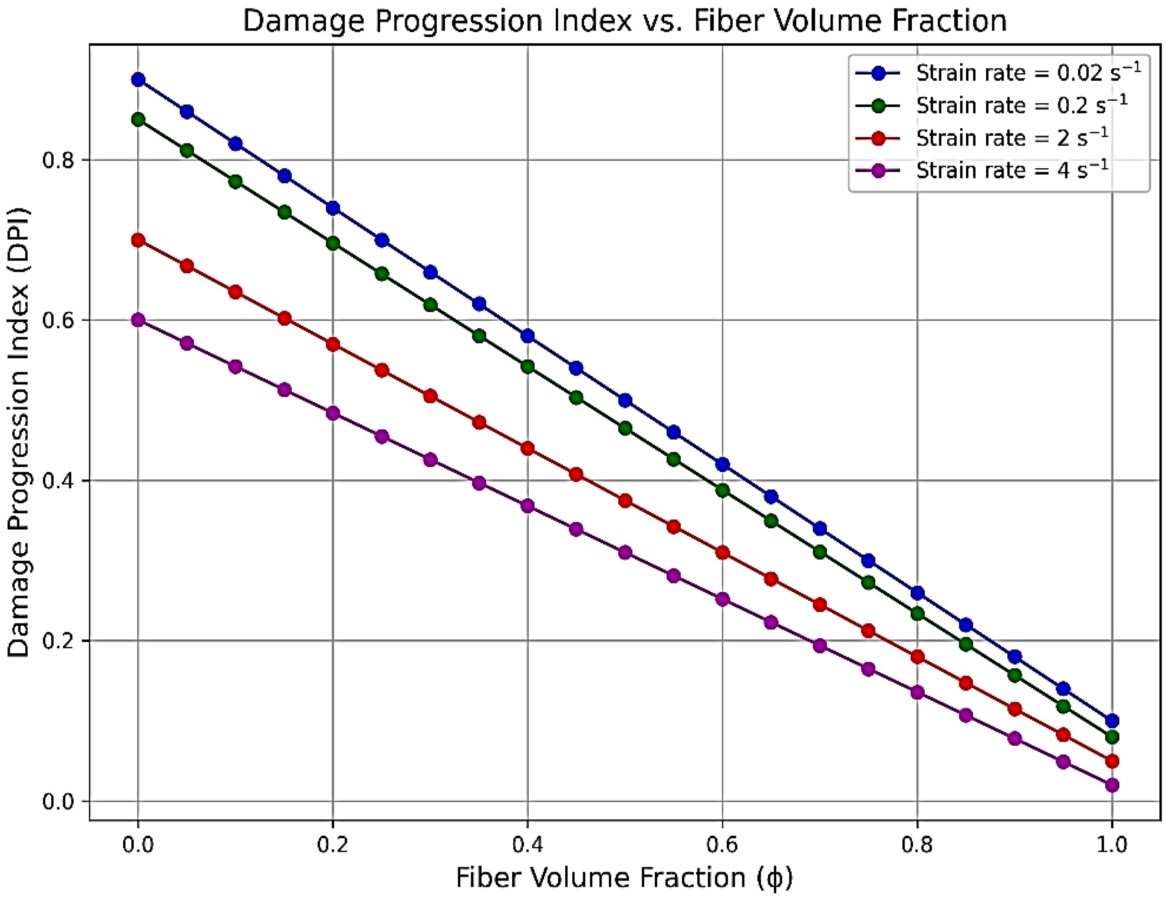

Fig 2 Variation of the Damage Progression Index (DPI) as a function of fiber volume fraction

In composite material design, fiber volume fraction is one of the most crucial parameters influencing mechanical properties such as elastic modulus, strength, and damage growth index. The provided graph clearly demonstrates how changes in fiber volume fraction (ϕ) affect the damage growth index at different strain rates. Fig 2 shows that the lifespan and safety of composite materials under quasi-static loading and various strain rates experience significant changes with variations in fiber volume fraction. As seen in the figure, the damage growth index consistently decreases with increasing fiber volume fraction across all strain rates. This behavior is expected, as in composite materials, an increase in fiber volume fraction typically leads to improvements in stiffness and toughness, thereby reducing the potential for damage under loading conditions.

At a strain rate of 0.02 s^{-1}, the highest damage growth values are observed, indicating that the material is less sensitive to damage under slower loading rates. Conversely, a strain rate of 4 s^{-1} results in the lowest damage growth, suggesting that the composite material behaves more vulnerably under faster loading rates. As the strain rate increases, the final value of the damage growth index decreases, and the curves converge towards lower levels. Fig 2 illustrates the effect of fiber volume fraction on the ultimate strength at different strain rates. The results show a significant increase in ultimate strength with an increase in fiber volume fraction, particularly at higher strain rates. This behavior may be attributed to the enhanced resistance of the fibers to external loads and the improved force transfer between the matrix and fiber phases To enhance the scientific credibility of this section, reference can be made to similar studies indicating that the effect of fiber volume fraction in composite materials can be attributed to various mechanisms, such as the reinforcement of the matrix-fiber bond and the reduction in damage propagation. Recent studies have also emphasized that these effects depend on factors such as fiber type, matrix composition, and the distribution of fibers within the composite structure.

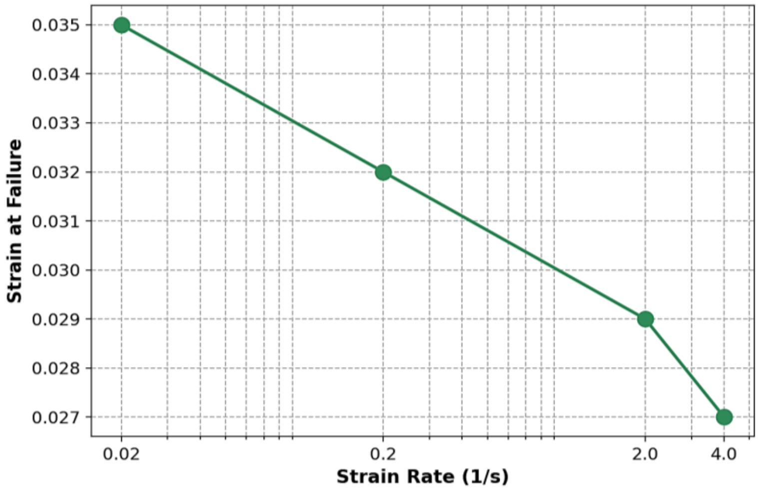

Fig 3 The effect of strain rate on fracture strain

Fig demonstrates the critical influence of strain rate on fracture strain in composite materials, revealing an inverse logarithmic relationship where increasing strain rates (0.02–4 s^{-1}) systematically reduce fracture strain from 0.035 (at 0.021 s^{-1}) to 0.027 (at 4 s^{-1}). This rate-dependent behavior, captured through numerical data, reflects the material's viscoplastic response: higher strain rates limit molecular rearrangement, promote localized stress concentrations, and shift failure modes toward brittle fracture (e.g., fiber-dominated vs. matrix-dominated failure), while lower rates enable greater plastic deformation. The consistent trend provides a foundation for predictive modeling of composite behavior under dynamic loading conditions, with direct implications for impact-resistant design and constitutive model development.

Investigation of Strain Rate Effects on the Elastic Modulus of Kevlar-Glass Hybrid Composites

Fig 3 presents the variations of longitudinal elastic modulus (E_1), transverse elastic modulus (E_2), shear modulus (G_{12}), and Poisson's ratio (ν_{12}) as functions of strain rate. The results demonstrate significant strain-rate dependence across all mechanical properties, with the longitudinal modulus exhibiting the most pronounced sensitivity.

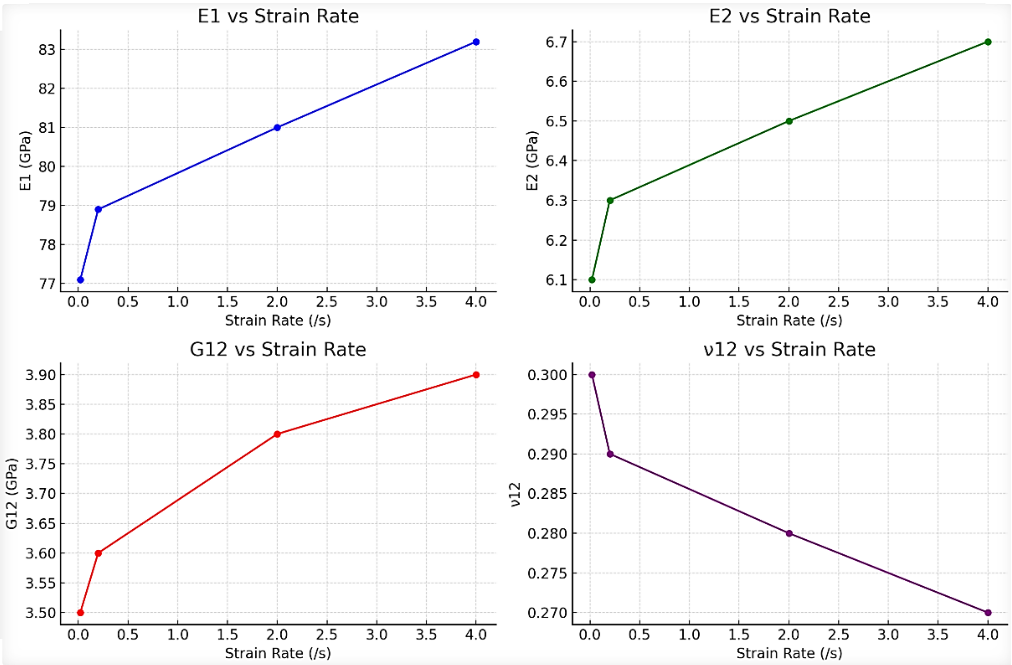

Fig 3 Strain Rate Dependence of Longitudinal (E_1) and Transverse (E_2) Elastic Moduli

Fig 3 demonstrates that both the longitudinal (E_1) and transverse (E_2) elastic moduli exhibit increasing trends with strain rate, confirming the material's strain-rate dependent behavior. The longitudinal elastic modulus (E_1), representing the fiber-direction stiffness, shows a significant increase from approximately 68 GPa at a strain rate of 0.2 s^{-1} to about 93 GPa at 4 s^{-1}, indicating pronounced strain-rate sensitivity along the fiber direction. Similarly, the transverse elastic modulus (E_2) displays an ascending trend, though with a less marked increase, suggesting that strain rate also influences the transverse elastic properties, primarily governed by matrix and interfacial characteristics. These results collectively demonstrate the rate-dependent nature of the studied composite material, with enhanced elastic properties at higher strain rates. Furthermore, as the strain rate increases from 0.5 to 4 s^{-1}, the shear modulus (G_{12}) shows a consistent rise, indicating improved shear stiffness under faster loading rates. This behavior stems from restricted mobility of polymer chains in the matrix phase, which enhances the material's resistance to shear deformation.

Conclusion

An increase in the fiber volume fraction (V_f) consistently leads to a reduction in the damage index across all evaluated models. This trend aligns well with the fundamental mechanics of composite materials, where a higher volume of fibers enhances the overall stiffness and load-bearing capacity of the structure. As the stiffness of the composite increases, stress tends to localize within the fiber phase rather than the matrix. Since fibers generally possess higher strength and damage tolerance compared to the matrix, this redistribution of stress reduces the overall susceptibility of the composite to progressive damage. Consequently, damage is less likely to propagate extensively through the matrix, resulting in a lower global damage index.

Interestingly, the proposed damage evolution model developed in the present study demonstrates greater sensitivity to variations in V_f when compared with the baseline or simplified models. This heightened sensitivity can be attributed to the model's ability to more accurately capture the micro-mechanical interactions between the fiber and matrix phases, particularly under conditions of stress concentration and localized deformation. Such precision in modeling allows for better prediction of the damage initiation and progression pathways as the fiber content increases, which is crucial for the design and optimization of high-performance composite materials.

In parallel, the results also indicate a positive correlation between fiber volume fraction and the ultimate strength of the composite. As V_f increases, a greater portion of the external load is transferred directly to the fiber network, which is the primary load-bearing constituent in most polymer matrix composites. This leads to a notable enhancement in the ultimate tensile or compressive strength of the material system. Moreover, the influence of strain rate is clearly observable: at higher strain rates, the ultimate strength increases. This behavior is consistent with the strain rate sensitivity typically observed in fiber-reinforced composites, where higher loading rates suppress certain damage mechanisms such as matrix micro-cracking and fiber-matrix debonding, thus allowing the material to sustain greater loads before failure.

Collectively, these findings underscore the critical role of fiber volume fraction not only in governing the stiffness and strength of the composite but also in influencing the dynamics of damage evolution under varying strain rates. The results also validate the robustness of the developed model in capturing these complex interdependencies, offering a reliable computational tool for the predictive design of advanced composite structures subjected to dynamic or impact loading condition.

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