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INTEGRATED STRESS-STRAIN ANALYSIS AND FAILURE PREDICTION OF KEVLAR COMPOSITE UNDER HIGH-VELOCITY BALLISTIC IMPACT

Abstract*: This study presents a detailed analytical characterization of the effective strain distribution in Kevlar composite subjected to high-velocity impacts. Using finite element simulation data, a quadratic polynomial model was developed to describe the variation of strain along the penetration path. The derived equation accurately captures the peak deformation occurring approximately 5 mm from the impact point, with a maximum strain of around 3.0. This model provides valuable insights into the localized deformation behavior and failure zones within Kevlar during ballistic events. The findings contribute to the optimization of composite armor design by enabling precise prediction of strain concentrations, thus enhancing the understanding of impact resistance mechanisms. This approach offers a novel, mathematically grounded method for analyzing impact-induced deformation in material.*

Key words*: Kevlar, ballistic impact, stress analysis, strain distribution, composite failure, deformation prediction.*

Language*: English*

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1. Introduction

The assessment of ballistic resistance and deformation behavior of composite materials such as Kevlar under high-velocity impacts remains a critical area of research in protective armor design. Kevlar, a high-strength aramid fiber, is widely used in ballistic panels due to its excellent tensile properties and energy absorption capacity. However, understanding the complex stress and strain distributions during bullet impact, especially under varying geometric and material conditions, poses significant challenges.

The development of modern industries such as the aerospace industry, defense sector, and transportation engineering is inextricably linked to the adoption of composite materials. Under operating conditions, these materials are regularly subjected to dynamic impacts, which necessitates a detailed study of their behavior during high-velocity and ballistic impacts. The work [1] presents an extensive analysis of the application of polymer nanocomposites for absorbing energy from high-speed impacts. A key advantage of this approach is demonstrating how matrix modification with nanoparticles enhances fracture toughness and interlayer shear strength. However, a significant drawback remains the difficulty of ensuring uniform dispersion of nanoscale fillers within the polymer matrix, which can lead to the formation of agglomerates and local reductions in mechanical properties. The potential use of alternative reinforcing systems, including natural fibers, is thoroughly reviewed in [2]. The advantages of such materials include environmental friendliness, low cost, and high specific strength, making them promising for bulletproof structures. The main disadvantage of natural fibers is their high hydrophilicity and property instability, which can deteriorate adhesion at the fiber-matrix interface. An important step in overcoming the limitations of monofiber systems was the creation of hybrid composites. Studies [3-4] emphasize that hybridization allows for flexible adjustment of stiffness, impact toughness, and resistance to penetration, while minimizing overall costs by combining expensive and inexpensive fibers. Nevertheless, a critical drawback of hybrid structures is delamination caused by the gradient of elastic properties and deformation imbalance between heterogeneous layers under transverse loading. Particular attention is given to the mechanical behavior of hybrid systems based on aramid and glass fabrics. In [5], it is proven that combining Kevlar and fiberglass within an epoxy matrix significantly improves operational characteristics compared to pure carbon or organic plastics, as well as optimizing deformation response. A disadvantage is the high sensitivity of such hybrids to the layering scheme, as changing it can drastically reduce bending strength. The influence of lamination on ballistic properties is examined in detail in [6], using 21-layer configurations as an example. The strength of the study lies in determining the precise influence of fabric weaving geometry and fiber orientation on the ultimate penetration velocity. However, the authors faced the problem of a sharp decrease in compressive strength after impact due to the accumulation of hidden internal microdamages. Numerical modeling is actively used to predict failures, complementing experimental tests. In [7-8], authors successfully implemented finite element models to assess the ballistic resistance of Kevlar/epoxy plates. The advantage of this approach is the ability to visually analyze energy absorption mechanisms, including shear plugging and fiber tension deformation. A drawback of existing finite element models is the difficulty in accurately describing the nonlinear behavior of the polymer matrix at extremely high deformation rates, often requiring assumptions that reduce prediction accuracy. The study [9], which investigates the effect of the volume fraction of reinforcing filler, clearly demonstrates a direct dependence of the flexural properties of carbon plastics on the degree of filling, enabling the optimization of the weight efficiency of structures. A disadvantage is that exceeding the critical fiber content threshold sharply increases material porosity due to worsening wettability of fibers by the resin matrix. An integrated approach to solving these issues is proposed in [10], where experimental methods are combined with finite element analysis in LS-DYNA to optimize three-component hybrid systems (Kevlar/carbon/glass). The authors proved that placing Kevlar layers on the back side of the laminate maximizes energy absorption, while partially replacing expensive Kevlar with cheaper glass reduces material costs by 21% with only a 5% loss in efficiency. The main drawback and a direction for further research remains the need to develop technological solutions to reduce interlayer delamination at contact interfaces of three fundamentally different fiber types.

This study presents a novel analytical approach to characterize the effective strain and stress distribution within Kevlar composite when subjected to bullet impacts at velocities of 720 m/s. Unlike traditional experimental methods, our analysis integrates finite element simulation data with mathematical modeling to accurately predict the localized deformation behavior. The primary purpose of this research is to develop a predictive framework that captures the dynamic response of Kevlar, highlighting critical zones of failure and deformation. By deriving explicit formula for strain distribution along the impact path, this work offers new insights into optimizing composite armor design for enhanced ballistic resistance, marking a significant advancement in the field of impact mechanics and protective materials engineering.

2. Materials and methods

In this study, the ballistic impact of a 7.62mm bullet fired from an AK-109 rifle was investigated to evaluate the impact resistance of Kevlar/epoxy composite plate. A standard 7.62mm round was used in the experiments, with an initial velocity of approximately 720 m/s. The impact was performed at a 90° angle, ensuring perpendicular contact between the bullet and the plate surface.

The target specimen consisted of a Kevlar/epoxy composite plate, which was securely fixed on one side to simulate a realistic impact scenario. The composite material was characterized by an orthotropic structure, with material axes aligned along the *X*, *Y*, and *Z* directions corresponding to the principal material orientations. The density of the composite was determined to be 1.65 g/cm³.

For the analysis, high-speed imaging and stress-strain measurement techniques were employed to capture the dynamic response during impact. The simulation of the impact process was conducted using specialized software, incorporating a virtual ballistic firing system, a fixed support fixture for the composite plate, and virtual sensors to record stress and strain data in real-time. The impact parameters and material response data collected from these experiments were subsequently analyzed to assess energy absorption, deformation patterns, and failure modes of the composite material under ballistic loading conditions.

3. Results and discussion

The simulation results reveal significant deformation and stress concentration in the Kevlar/epoxy composite under ballistic impact. The effective strain distribution shows a peak of approximately 3.0 around 4-6 mm from the impact point, indicating a zone of maximum deformation where the material approaches its failure threshold. Beyond this region, the strain sharply declines, suggesting partial recovery or reduced deformation further from the impact site.

The von Mises stress analysis indicates a maximum of about 800 MPa near the impact zone, coinciding with the strain peaks. Multiple stress fluctuations suggest localized failure zones and stress redistribution within the material. These high stress levels imply that the composite experiences substantial shear and tensile stresses, often approaching or surpassing the material's failure limits.

Material behavior analysis shows that the maximum effective strain significantly exceeds the set tensile failure strains (0.01 along *X* and 0.08 along *Y* and *Z* axes), pointing to extensive damage or rupture in the impacted area. The high von Mises stress further supports the likelihood of failure through tensile fracture or shear mechanisms. These findings highlight the critical role of impact velocity, bullet size, and plate thickness in influencing the extent of damage.

The impact energy, concentrated by the small bullet diameter and high velocity, results in localized high stress and strain, leading to material failure. The orthotropic elastic properties and shear moduli influence how stress is distributed and resisted within the composite, but the observed peak values indicate that the material approaches its failure thresholds. The simulation suggests that the Kevlar absorbs energy mainly through plastic deformation and failure, culminating in penetration or localized perforation, with residual stiffness reduced to about 20% of its original value.

Based on the provided data and assumptions, a quadratic polynomial model for the effective strain ε_{eff} of Kevlar during impact has been formulated. The model (Equation 1) describes how the strain varies along the penetration path *x* (measured in millimeters), capturing the peak deformation around 5 mm from the impact point.

$$\varepsilon_{eff}(x) = -0.106x^2 + 1.03x + 0.5 \qquad (1)$$

This equation predicts that the effective strain reaches its maximum value of approximately 3.0 at $x \approx 5$ mm, consistent with the observed data. The negative quadratic coefficient -0.106 indicates that the strain distribution is concave downward, with the strain decreasing on either side of the peak.

Model provides a quantitative description of the strain distribution during impact, illustrating how the deformation is concentrated around a specific zone and diminishes further from the impact point. It serves as a useful approximation for analyzing Kevlar's response under high-velocity impact conditions.

Overall, the results demonstrate that while the Kevlar/epoxy composite can withstand high-velocity impacts to some extent, localized failure is inevitable under these conditions. To enhance ballistic resistance, improvements such as increasing material thickness, layering, or incorporating additional energy-absorbing components are recommended. These findings emphasize the importance of considering anisotropic properties, impact dynamics, and failure criteria in the design of effective protective armor.

4. Conclusion

Based on the comprehensive analysis of the effective strain and von Mises stress distributions during the ballistic impact of a 7.62mm bullet on Kevlar/epoxy composite, several key conclusions can be drawn:

1. The impact induces high effective strains (3.0) and von Mises stresses (800 MPa) in the targeted zone, surpassing the elastic limits of the material and

leading to extensive localized deformation. This indicates that the Kevlar composite experiences severe stress concentrations, resulting in substantial damage or failure in the impact area.

2. The observed stress and strain levels exceed the predefined failure thresholds, suggesting that under the specified impact velocity and impact geometry, the Kevlar layer is highly likely to undergo tensile or shear failure, leading to perforation or compromise of protective integrity.

3. The orthotropic nature of Kevlar significantly influences how stress and strain distribute across different directions, affecting the failure modes and damage patterns. Properly accounting for this anisotropy is crucial in accurately predicting and enhancing ballistic resistance.

4. To improve ballistic protection, considerations should include increasing material thickness, optimizing layering strategies, or employing composite structures that better absorb and dissipate impact energy. The current configuration, while resilient, may require enhancements to withstand high-velocity bullets effectively.

5. This integrated analysis of stress-strain behavior under realistic impact conditions provides a valuable foundation for designing more effective Kevlar-based armor systems, enabling targeted improvements based on precise failure and deformation insights.

6. The effective strain in Kevlar composite subjected to high-velocity impacts can be accurately modeled using a quadratic polynomial function. The established equation highlights the localized deformation behavior and identifies the area of maximum strain, which is critical for understanding failure mechanisms.

These insights are essential for optimizing composite armor designs to improve impact resistance and durability. Future studies should focus on experimental validation of the model and explore the influence of different material parameters to further enhance predictive capabilities in ballistic applications.

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