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Numerical Analysis of the Low-Velocity Impact Behavior of Different Kevlar-29/Epoxy Lamination Structures

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ABSTRACT

In this study, a low-velocity impact test was numerically simulated on Kevlar-29/Epoxy laminates with dimensions of 100 × 100 mm and a thickness of 6 mm, arranged in $[0/45/90]_4$, $[0/30/60/90]_3$, and $[0/90]_6$ orientation sequences using the LS-DYNA software. The impact loading was applied by a 6 mm-diameter impactor with a mass of 15 kg striking the laminates at a velocity of 5.0 m/s. The maximum force values varied depending on the lay-up sequence, and the highest peak force was obtained in the $[0/30/60/90]_3$ configuration with 45 kN. In the energy–time analysis, it was observed that the total energy transferred during the impact was approximately 187.5 J for all three configurations. This impact result suggests using isotropic approach paving rows using different stacking sequence to maximize energy absorption and increase damage tolerance.

Farklı Kevlar-29/Epoksi Laminasyon Yapılarının Düşük Hızlı Darbe Davranışının Sayısal Yöntemlerle Analizi

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ÖZET

Bu çalışmada, LS-DYNA yazılımı kullanılarak $[0/45/90]_4$, $[0/30/60/90]_3$ ve $[0/90]_6$ yönelim dizilimleriyle yerleştirilmiş, 6 mm kalınlığında ve 100 × 100 mm boyutlarında üretilmiş Kevlar-29/Epoksi laminelere düşük hızlı darbe deneyi sayısal olarak simüle edilmiştir. Laminelerin üzerine, 6 mm çapında ve 15 kg kütlesine sahip vurucu bir cismin 5.0 m/s hızla uygulanmasıyla darbe yüklemesi gerçekleştirilmiştir. Maksimum kuvvet değerleri elyaf dizilimi bağlı olarak değişmiş olup, $[0/30/60/90]_3$ diziliminde 45 kN ile en yüksek tepe kuvveti elde edilmiştir. Enerji–zaman analizinde, üç konfigürasyonda da darbe sırasında aktarılan toplam enerjinin yaklaşık 187.5 J olduğu görülmüştür. Bu darbe sonucu, enerji sönümleme maksimize etmek ve hasar toleransını artırmak için farklı serim yöntemlerini kullanarak izotropik yaklaşıma sahip serim sıralarının kullanılması önermektedir.

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INTRODUCTION

With the acceleration of technological advancements, traditional engineering materials are being replaced by advanced materials that exhibit superior mechanical, physical, and chemical properties. In particular, research focused on improving ballistic performance and impact resistance in military applications is of great importance for detecting material damage, optimizing new designs, and validating strength analyses. In this context, composite materials developed for such purposes are widely used in the defense industry, the aerospace sector, armored vehicle systems, and the automotive industry(ÖZTEMÜR et al., 2024).

Composite materials are heterogeneous structures obtained by combining two or more constituents in specific proportions without dissolving into one another. Owing to their low specific weight and high mechanical strength, they exhibit superior performance compared to conventional materials. Due to these advantageous properties, composite materials are widely used in various fields such as military armored vehicles, ballistic protection systems, aerospace structures, and the automotive industry. In such applications, it is critical for the components to withstand objects impacting at high velocities. Therefore, before proceeding to the manufacturing stage, various impact and ballistic tests are conducted to evaluate the performance of the material (Mecitoğlu et al.2020). In fiber metal laminates (FMLs), the most commonly used metal is aluminum, and the reinforcing fibers are typically Kevlar or glass fibers. FMLs reinforced with glass fibers and those reinforced with Kevlar fibers have been extensively studied in terms of their potential applications in aircraft structural components(Wu & Yang, 2005). However, the damage and strength predictions of composite materials have not yet been fully and universally defined. Therefore, various damage criteria have been developed, taking into account different loading conditions and material types, and have become widely used in the literature.

Kevlar fiber is a lightweight and tough aramid fiber with high tensile strength and resistance to abrasion. Composites reinforced with Kevlar fibers are commonly used in materials subjected to high friction conditions. Kevlar fibers possess the capability to withstand high-velocity impacts and have a high specific strength, making them more efficient than metals and ideal for use in various structural and aerospace applications (Benli, 2025).

In the defense industry, Kevlar fiber-epoxy composites are utilized in the production of protective helmets and body armor. With technological advancements, these composites can be manufactured using different approaches and methods, and they are now employed across a wide range of sectors (Altıntaş, Hayri, 2021). In particular, properties such as vibration resistance, fatigue durability, and thermal stability are among the primary advantages of Kevlar fiber-epoxy materials in the aerospace industry (Iç et al., 2019).

Tolunay Dağ (Dağ, 2024) conducted studies on the optimization of impact behavior and mechanical properties of reinforced panels used in aircraft structures. In this study, the effects of mechanical properties such as stacking direction, thickness, number of layers, and layer thickness on the impact behavior of panels were investigated using Artificial Neural Networks (ANN) and the Taguchi L9 method to optimize impact-induced deformation and vibration responses.

T. Jambhulkar and colleagues (Jambhulkar & Sahu, 2024) aimed to improve the energy absorption performance of polymer composite laminates by varying the stacking sequence of to enhance impact damage resistance. Considering various projectile shapes suitable for low-velocity impact applications, the total deformation of the optimized stacked [K/K/G/G/K] composite was evaluated. The assessment provides insights into the properties of hybrid composite laminates and can guide the development of more effective materials for impact protection.

Mingling Wang and colleagues (Wang et al., 2024) investigated Is this statement true? Kevlar has a continuous structure and high toughness. Wang the stiffening mechanisms that enhance the response and impact resistance of Kevlar and Carbon Fiber Reinforced Polymer (CFRP) structures subjected to quasi-static indentation (QSI) and low-velocity impact (LVI) loading. They compared energy absorption under static and dynamic loading conditions. The study concluded that, as the toughness ratio increases in Kevlar hybrids, the static energy absorption of hybrid laminates gradually decreases, whereas dynamic energy absorption increases. Consequently, under dynamic loading, damage initiates on the non-impacted surface and propagates toward the impacted surface (Samsur et al., 2018).

G. Gruben and colleagues (Gruben et al., 2017) examined the behavior and failure of steel plates subjected to transverse loading on marine platforms. By performing low-velocity dynamic and quasi-static tests on the plates, they demonstrated that although the tests exhibited greater displacements at the point of fracture, they provide a valuable reference for impact loading scenarios.

Gin Boay Chai and his team conducted results of maximum damage modes using fiber-metal laminated panels, two different reinforced plastics, using a weight drop testing device (Zhu & Chai, 2012).

In this study, composite Kevlar plates were characterized using MAT55 material modeling, meeting the Chang-Chang and Tsai-Wu criteria. The laydown method was found to have a significant effect on impact behavior. The force curves examined the maximum stiffness of the structure under impact, with the alignments achieving the highest peak force. Displacement-time and velocity-time curves indicate that the maximum displacement varies depending on the laydown pattern. Energy-time plots revealed that all samples received similar impact energy, but the configuration that most effectively absorbed the energy was the one used. These findings confirm that multidirectional fiber alignments improve stress distribution and increase impact resistance.

First Level Subheading

First level subheadings should be capitalized, bold, in Times New Roman font and 11-point font size. A 12k space should be defined before headings. Headings and paragraphs should start with a 1cm indent. Line spacing should be 1.15k. There should be a 6k space above each paragraph. You can do these operations using the line spacing menu.

Second Level Subheading

Second-level subheadings should be capitalized, bold, italic, Times New Roman font and 11-point font size. A space of 12 spaces should be defined before headings. Headings and paragraphs should start with a 1cm indent. Line spacing should be 1.15k. There should be a 6k space above each paragraph. You can do these operations using the line spacing menu.

Third Level Subheading

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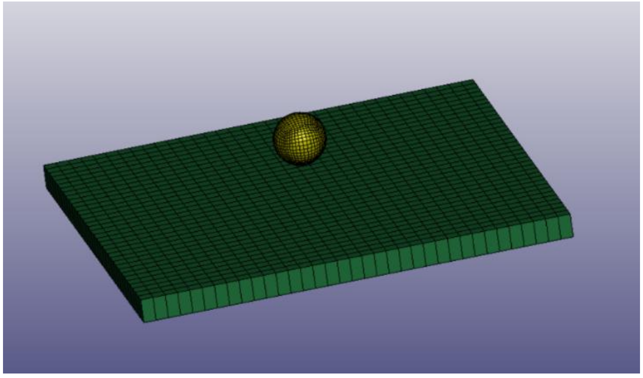
METHOD

In this study, three different methods of laying Kevlar-29/Epoxy laminated composite plates were used to evaluate the damage mechanisms and structural reactions caused by low-speed impact loads, critical damage types and finite element analysis in impact-affected FML (Azhdari et al., 2021).

The impact load was applied to a 100×100 mm square Kevlar-29/Epoxy laminate consisting of twelve layers using a rigid spherical impactor with a radius of 6 mm at a velocity of 5 m/s. The impact event was completed within 0.007 seconds. As boundary conditions, two opposite edges of the laminate were fully constrained in all degrees of freedom, while the remaining edges were left free. The LS-DYNA model of the composite material and impact mechanism is presented in Figure 1.

Figure 1
Perspective View of 3D Modeled Impactor and Laminated Composites



Material Selection

A composite material is defined as a new material formed by the combination of at least two different materials with specific chemical or physical properties at the macro scale. Generally, they work together to provide higher strength, stiffness, impact resistance, or reduced weight. Composite materials can be classified into five categories based on the form of the reinforcement used: particulate-reinforced, fiber-reinforced, laminar, laminated, and filled composites. Within the scope of this study, Kevlar fiber emerges as a prominent aramid reinforcement material widely preferred in ballistic and high-performance composite applications, offering superior specific strength due to its high tensile strength and low density. Its ability to effectively dissipate impact energy through micro-fracture mechanisms, combined with resistance to heat and flame, further enhances its applicability. The material modeling was performed using MAT-55 ENHANCED COMPOSITE DAMAGE. The mechanical properties of Kevlar-29/epoxy are presented in Table 1.

Table 1
Kevlar-29/ Epoxy Mechanical Properties

MATERIAL PROPERTY	Values	Units	Symbol
Density	1259	kg/m^3	ρ
Modulus of Elasticity (Longitudinal Direction)	2.05e10	Pa	E_1
Modulus of Elasticity (Transverse Direction)	2.05e10	Pa	E_2
Poisson Ratio	0.21	-	v_{12}
Poisson Ratio	0.33	-	v_{12}
Poisson Ratio	0.33	-	v_{12}
Shear Modulus	7.70e8	Pa	G_{12}
Longitudinal Compressive Strength	5.95e8	Pa	x_c
Longitudinal Tensile Strength	5.95e8	Pa	x_T
Transverse Compressive Strength	6.00e9	Pa	Y_c
Transverse Tensile Strength	6.00e9	Pa	Y_T
Shear Strength	7.70e7	Pa	S_c
Maximum strain for the matrix	2.902e+18		DFAILM
Maximum shear strain	1.000e+15		DFAILS
Maximum strain for fiber compression	-2.902e+18		DFAILC
Maximum strain for fiber tension	2.902e+18		DFAILT

The plate material parameters used in this study were determined based on the values reported by (Guo et al., 2022)

The material properties of the striker defined by the MAT-20 RIGID material function are given in Table 2.

Table 2
Mechanical Properties of the Impact Mass

MATERIAL PROPERTY	Values	Units
Density	1658	kg/ m^3
Young's Modulus	2.07e11	GPa
Ratio Poisson	0.3	-

In order to use the MAT-055 material card, it must satisfy the equation in Equation 1.0. If this equation is not met, the numerical simulation cannot be completed.

$$v_{12} = v_{21} * E_1 \,/\, E_2 \,,\, v_{12} * v_{21} < 1 \qquad (1.0)$$

In this study, strain-based damage criteria covering fiber and matrix damage modes for the Kevlar-29/epoxy composite were calculated using literature-based equations and are presented in Equations (1.1)–(1.4). (Master's Thesis, 2024).

$$\text{DFAILM}=\frac{y_c}{E_2} \qquad (1.1)$$

$$\text{DFAILS}=\frac{s_c}{G_{12}} \qquad (1.2)$$

$$\text{DFAILC}=-\frac{x_c}{E_1} \qquad (1.3)$$

$$\text{DFAILT}=\frac{x_T}{E_1} \qquad (1.4)$$

The interaction between the impactor mass and the composite structure was modeled using the AUTOMATIC NODES TO SURFACE contact algorithm using an impact velocity of 5 m/s. Analyses were performed with the LS-DYNA solver, and the resulting outputs were recorded. For post-solution data evaluation, the results in binary database format were visualized in three dimensions using D3PLOT, and these images were analyzed in detail using LS-PrePost software (Dağ et al., 2022). During the investigation, the dynamic response of the structure during the impact, interlaminar separation behavior, local stress concentrations, and the resulting deformation modes were evaluated. Additionally, for a more comprehensive analysis of the solution, GLSTAT, MATSUM, and RCFORC ASCII data files were examined to obtain additional information on energy balances, material response, and contact forces.

RESULTS

Using LS-DYNA software, a low-velocity impact test was simulated on 6 mm-thick, 100 x 100 mm Kevlar-29/Epoxy laminates arranged with stacking sequences of $[0/45/90]_4$, $[0/30/60/90]_3$, and $[0/90]_6$. The simulations provided results for force, displacement, velocity, and energy variations.

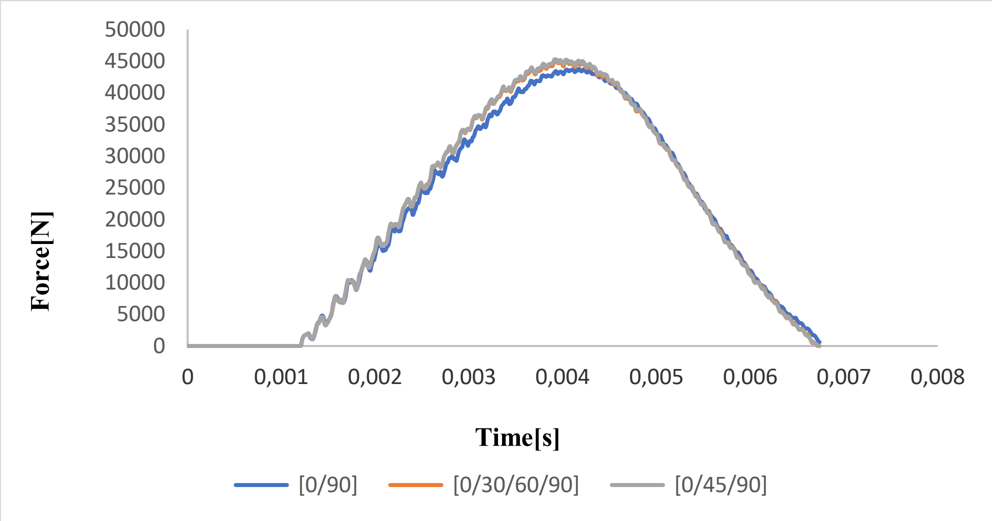
Force - Displacement Response

At the initial moment when the impacting mass contacts the plate, fluctuations in the force-time curve occur due to the stresses generated at the interfaces. These fluctuations, seen in Figure 2, are a result of the Hertzian behavior that occurs during contact. According to the obtained data, the specimen with the [0/30/60/90] laydown sequence achieved the highest maximum impact resistance.

This demonstrates that the [0/30/60/90] laydown sequence, which is closer to direction-independent behavior, has a superior capacity to absorb impact energy and control propagated stresses compared to the [0/90] or [0/45/90] laydown sequences. Laydown sequences with a greater number of different angles propagate local fiber fractures and matrix cracks, increasing overall damage tolerance.

Figure 2

Force Time Curve for Different Layer Placement Configurations

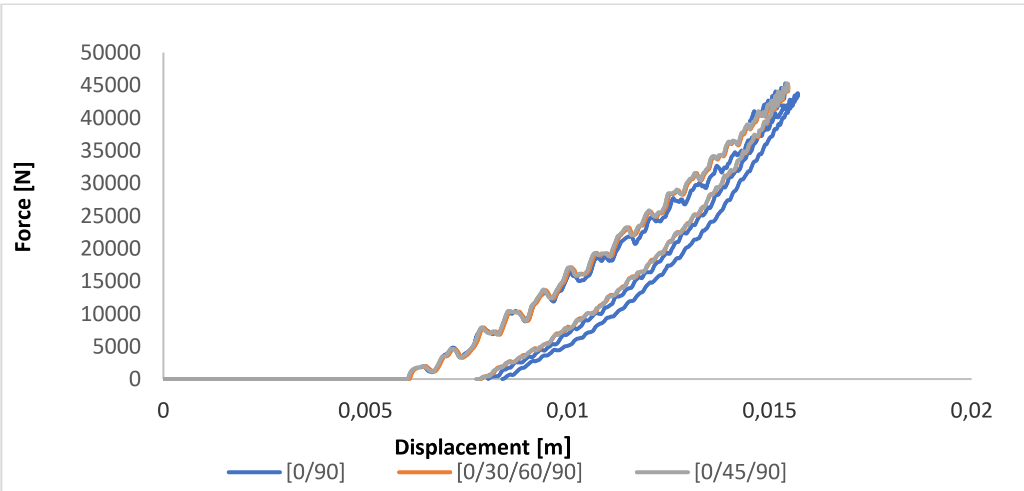


Furthermore, the fact that all three samples exhibit very similar impact durations and overall curve shapes indicates that the effect of the stacking sequence on stiffness is less significant than its effect on the maximum load-bearing capacity at this impact energy level. The mechanical response of laminated composite specimens made from Kevlar-29/Epoxy fibers under low-velocity impact loading is presented in the Force-Displacement curves in Figure 3.

The curves return almost exactly to the starting point after loading, forming a closed loop, clearly demonstrating that no complete puncture failure or permanent macroscopic structural failure occurred in the specimens at the applied impact energy level. This closed-loop form indicates that the material absorbed the energy largely through elastic deformation and damage mechanisms, with some of the energy being returned by the rebound of the impacting mass.

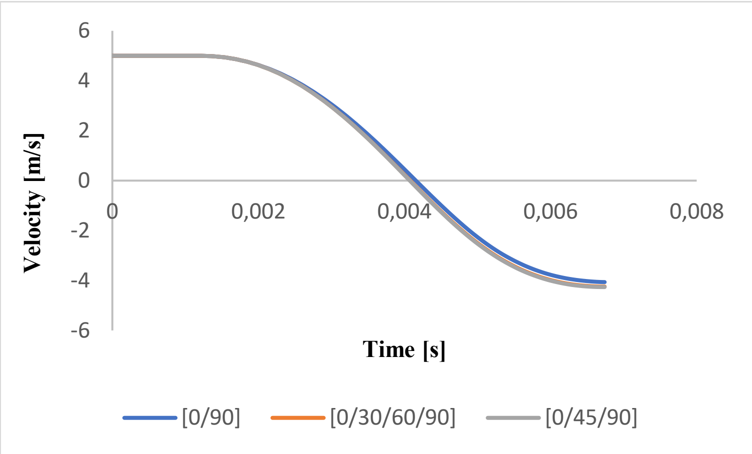
Figure 3

Displacement- Force Curve for Different Layer Layout Configurations



Keeping the impactor's speed constant increases the amount of displacement occurring in the composite structure. It is observed that the maximum displacement value of the sample is achieved when the impactor's speed is zero during the impact performed with three different layer layout configurations. Figure 4 shows the velocity-time curves and the velocity-displacement curves obtained as a result of the impact applied for different layer layout configurations.

Figure 4
Velocity–Time Curves for Different Layer Placement Configurations

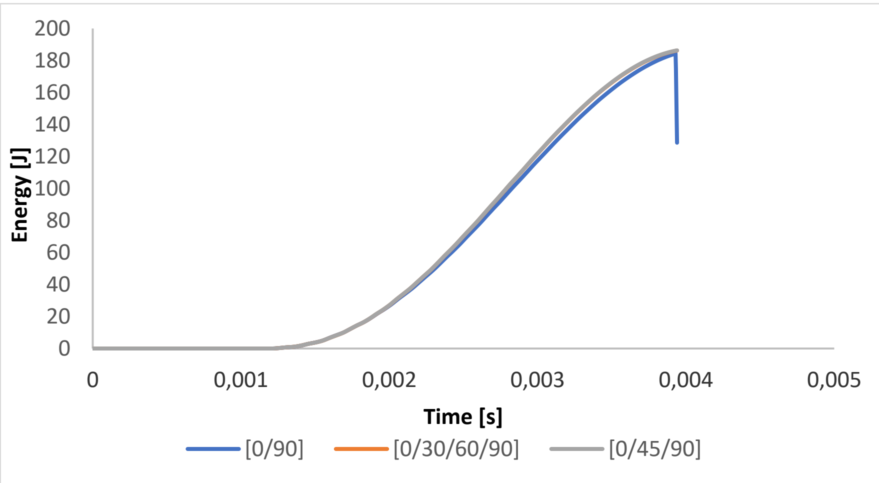


Energy Absorption

Figure 5 presents Energy-Time curves showing the energy absorption during an impact event for composite specimens with different layer laydown sequences. The peak in the graph represents the moment when the applied impact energy is transferred to the specimen and maximum force is reached. The amount of energy dissipated at this peak is a key parameter characterizing a material's resistance to impact damage.

During the three deployments, a maximum energy value of around 187.5 J was reached during an interval where the impact terminated around 0.0039 s and energy transfer ceased. This indicates that all samples experienced a similar initial impact energy. The slope and shape of the curves to the peak are nearly identical for all three configurations, demonstrating that the energy transfer rate is similar regardless of deployment order.

Figure 5
Energy Time Curve for Different Layer Layout Configurations



Effective Stress Distribution on Laminate

When examining the stress values for low-velocity impact, an increase in stress values was observed due to changes in layer layout configurations. Effective Stress Distribution analyses reveal the critical impact of the laydown sequence on stress concentration and distribution. The use of diagonal laydowns distributes the stress over a larger volume, reducing local stress peaks in potentially damaged areas, thus optimizing the composite's overall impact resistance and energy absorption capacity.

Figure 6

Effective Stress Distribution in [0/45/90]$_4$ Laminates After Impact

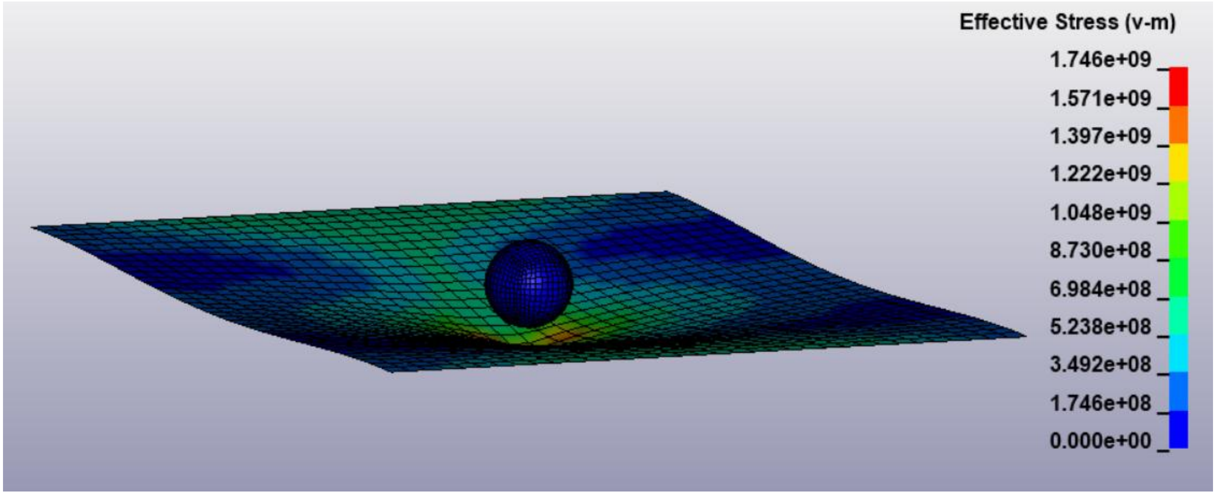


Figure 7

Effective Stress Distribution in [0/30/60/90]$_3$ Laminates After Impact

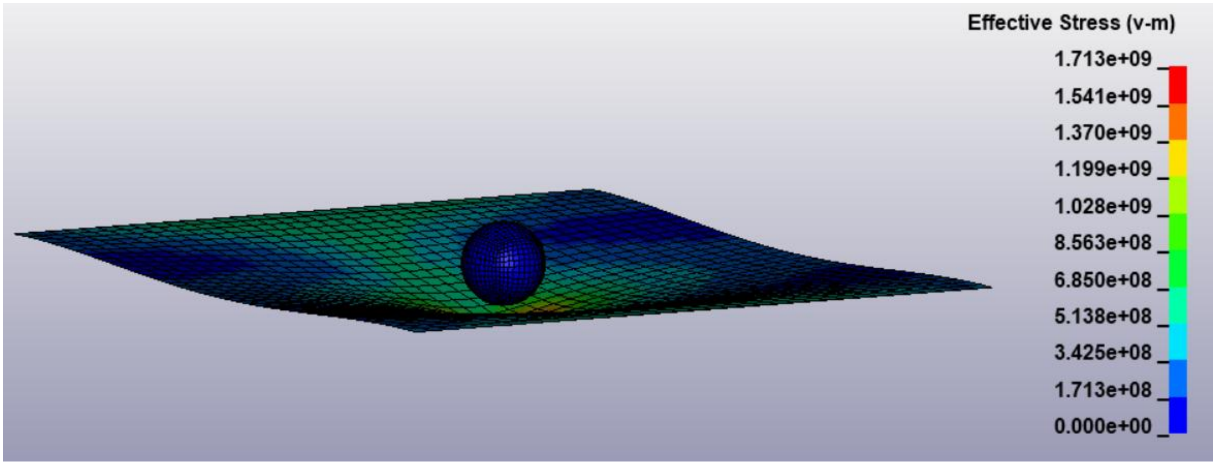
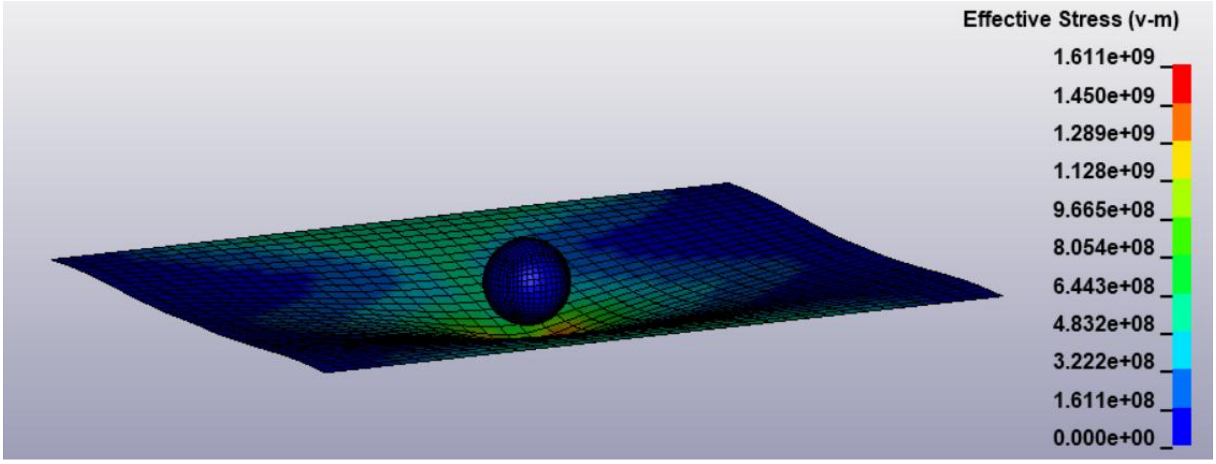


Figure 8
Effective Stress Distribution in $[0/90]_6$ Laminates After Impact



CONCLUSION

It was confirmed that complete perforation did not occur in any of the tested samples, and that the applied impact energy was mainly dissipated through matrix cracking and delamination mechanisms. Although the energy–time curves exhibit similar trends for all stacking sequences, clear differences were observed in the force response and damage evolution behavior. The $[0/30/60/90]_3$ stacking sequence exhibited the highest maximum contact force ($F \approx 45$ kN) and greater structural stiffness compared to the other configurations, indicating a more effective force transfer capability. Effective stress distribution analyses further demonstrate that multi-angle stacking sequences promote a wider stress distribution and reduce localized stress concentrations, thereby delaying damage initiation and limiting delamination growth. These results indicate that quasi-isotropic stacking sequences such as $[0/30/60/90]_3$ do not necessarily absorb significantly more energy, but instead optimize load redistribution and damage tolerance, leading to improved impact resistance under low-velocity impact conditions.

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EXTENDED ABSTRACT

Introduction: The introduction section serves as the entry point to the research, providing a comprehensive overview of the study's context, rationale, and objectives. It begins by contextualizing the research topic within existing literature and identifying gaps, controversies, or areas that require further exploration. By reviewing prior studies and establishing the significance of the research problem, the introduction sets the stage for the current investigation. Furthermore, it outlines the specific aims, objectives, or research questions addressed in the study, thereby guiding the reader's understanding of its scope and purpose. Through a well-crafted introduction, researchers can effectively engage readers, justify the need for their study, and lay the groundwork for subsequent sections.

Method: The method section provides a detailed account of the research design, methodology, and procedures employed to address the study's objectives. It elucidates key aspects such as the study's design (e.g., experimental, correlational, qualitative), sampling procedures, participant characteristics, data collection methods (including instrumentation and materials), and data analysis techniques. By transparently documenting these methodological details, researchers enable readers to evaluate the validity, reliability, and generalizability of their findings. Moreover, the method section ensures research replicability by furnishing sufficient information for other scholars to replicate or build upon the study. Clear and systematic reporting of the methodological framework enhances the credibility and rigor of the research endeavor.

Findings: In the findings section, researchers present the empirical data collected during the study and report the outcomes of their analyses. This section typically begins with a descriptive summary of the data, including relevant statistics, frequencies, or distributions. Subsequently, researchers present the results of inferential statistical analyses, hypothesis testing, or thematic analysis, depending on the study's design and objectives. Data may be organized into tables, figures, or textual descriptions to facilitate comprehension and interpretation. Through the systematic presentation of findings, researchers enable readers to discern patterns, trends, or associations within the data, thereby supporting the study's conclusions and implications. It is essential to maintain clarity, accuracy, and objectivity in reporting findings, avoiding unwarranted interpretations or exaggerations.

Discussion: The discussion section offers a critical analysis and interpretation of the study's findings within the broader context of existing knowledge and theoretical frameworks. Researchers engage in a reflective dialogue, examining the implications, significance, and limitations of their findings. They contextualize their results by comparing them with prior research, identifying consistencies, discrepancies, or novel insights. Additionally, researchers explore potential explanations for observed patterns or phenomena, considering alternative interpretations or confounding factors. It is crucial to acknowledge and address any limitations or constraints inherent in the study, such as methodological shortcomings, sample biases, or data constraints. Furthermore, researchers speculate on the practical implications of their findings, offering recommendations for future research directions or practical interventions. The discussion section serves as the intellectual culmination of the research endeavor, synthesizing empirical evidence with theoretical insights and advancing scholarly discourse within the field.

Conclusion: The conclusion section encapsulates the key findings, contributions, and implications of the study, providing a concise summary and synthesis of the research journey. Researchers reiterate the main findings and underscore their significance in addressing the research problem or fulfilling the study's objectives. They reflect on the broader implications of their work, highlighting its theoretical, practical, or societal relevance. Moreover, researchers articulate the study's contributions to knowledge, identifying novel insights, methodological advancements, or theoretical refinements. Concluding remarks may also address unresolved questions, lingering uncertainties, or avenues for future inquiry. By offering closure and perspective, the conclusion section affirms the study's significance, invites scholarly dialogue, and inspires further exploration of the research topic.

Recommendation: The recommendations section offers actionable suggestions or proposals based on the study's findings and insights. Drawing upon the implications identified in the discussion section, researchers provide guidance for practitioners, policymakers, or other stakeholders. These recommendations may pertain to practical interventions, policy changes, or future research initiatives aimed at addressing the identified issues or capitalizing on opportunities identified by the study.