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Analysis of Impact Load on Fiber Composite Structures: A Study of Laminate Composite Materials

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Abstract

This study investigates the impact of low-velocity forces on laminated composite structures, specifically focusing on the damage mechanisms and failure criteria associated with fiber-reinforced polymer composites (RPC). Low-velocity impacts, often undetectable to the naked eye, can lead to significant structural degradation, including matrix cracking and fiber fracture, which ultimately compromise material stiffness and integrity. Utilizing a combination of experimental and numerical methodologies, this research aims to elucidate the critical parameters influencing damage in composite laminates subjected to impacts ranging from 3 to 5 m/s.

The investigation employs advanced finite element modeling alongside experimental tests to assess the mechanical responses of composite plates with varying thicknesses and configurations. Key findings reveal that the mass and velocity of the impacting object, as well as the dimensions of the composite plates, play pivotal roles in determining damage thresholds. The study introduces a modified Hashin failure criterion tailored for bidirectional woven fibers, enhancing the accuracy of damage predictions in laminated composites.

Results indicate that while impactor mass has a minimal effect on the resistance of laminated plates to low-speed impacts, understanding the interplay between various mechanical properties is essential for optimizing design and performance. The findings contribute valuable insights for engineers in selecting appropriate failure criteria and designing safer, more efficient composite structures for industrial applications. This research underscores the necessity of integrating both experimental data and numerical simulations in developing robust assessment methodologies for composite materials subjected to dynamic loading conditions.

Keywords: Composite Laminates, Impact Tests, Damage, Structural analysis, Failure Criteria, Hashin Modified.

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Introduction

Damage resulting from low-velocity impacts is rarely discernible to the unaided eye. Due to the challenges in identifying such damages, the hazards associated with low-velocity impacts on composite materials are considered to pose significant risks. Generally, the primary manifestations of damage encompass matrix cracking and fiber fracture prior to the occurrence of delamination. Such damage precipitates a considerable decline in the stiffness of the affected material and, by extension, the entire structural assembly. This decline in stiffness may even lead to catastrophic failure. Consequently, it is imperative to develop methodologies that enhance the assessment of composite material structures subjected to low-velocity impacts. The assessment of damage from low-velocity impacts has primarily been conducted through the application of the finite element method (FEM). Lakshminarayana and Murthy [1]; along with Luo et al. [2] executed a dynamic analysis of a structural entity via a commercial software application to predict material damage without incorporating progressive failure analysis. Zhao and Cho [3] investigated the onset of damage in a composite material utilizing eight-noded shell elements. Ganapathy and Rao [4] explored damage within a laminated curved shell element characterized by double curvature, possessing 48 degrees of freedom. Li et al. [5, 6] proposed a numerical model that simulates the low-velocity impact phenomenon based on a Mindlin plate element with nine nodes. Sahli et al. [7] presented a dynamic approach to the boundary element method for the examination of stress and failure criteria in anisotropic thin plates. Laminated reinforced polymer composites (RPC) demonstrate an exceptional amalgamation of stiffness, strength, and low weight, rendering them highly advantageous for structural applications. Structural efficiency is articulated as the ratio of strength to density or stiffness to density. In comparison to conventional materials such as aluminum alloys, steel, or titanium alloys, reinforced polymer composites can provide superior structural efficiency. Furthermore, a notable advantage of RPC laminates lies in their anisotropic characteristics, which empower engineers to customize material properties in conjunction with the geometric and functional dimensions of the structure. Thus, it is feasible to achieve the anticipated performance, facilitating the optimization of the weight function concerning the fiber orientation of the laminate and the designated design load [8]. According to Icardi [9], composite laminates are acknowledged as exceptionally appropriate materials for a plethora of structural applications. He observes that although these materials are deficient in ductility and exhibit constrained strain energy capabilities, they possess the capacity to effectively dissipate substantial quantities of energy through their various local failure mechanisms. This study delineates the material characteristics of the laminas employed in the impact test specimens. The comprehensive experimental campaign, in conjunction with the data processing methodology utilized for the low-speed tests, is expounded upon. With regard to numerical simulation, a variety of methodologies and configurations pertaining to numerical models are scrutinized. The design of structures conventionally adheres to a deterministic approach. Nevertheless, this design paradigm may not be optimal for composite materials, given the inherent variability in their mechanical properties. There exist established tools that can accommodate variations in both mechanical attributes and loading conditions. To leverage these tools effectively, a profound comprehension of the structure's failure mechanisms is imperative. The predominant types of loads encountered by an industrial structure encompass accidental impacts and fatigue stresses. The preliminary phase of this investigation entails examining the mechanical responses of composite structures subjected to low-velocity impacts (ranging from 3 to 5 m/s) with considerable mass (between 2.5 and 7 kg). Impact solicitation constitutes a multifaceted problem characterized by numerous parameters. The geometry, mass, and velocity of the impactor, as well as the dimensions of the composite plate and the boundary conditions [1-3] can delineate it. The central inquiry pertains to the identification of the critical parameters. One methodology for quantifying the influence of various factors on one or more outcomes is through the application of experimental design techniques. This enables the evaluation of multiple variables and the discernment of the most significant ones with a minimal number of experiments. A factorial and Doehlert matrix were utilized for the laminated composites. The evolution of responses concerning the variables is articulated through straightforward mathematical expressions (empirical polynomials), albeit these are not derived from fundamental physical principles. The objective is to provide tools for sizing composite structures; however, it is crucial to underscore that these tools will be applicable exclusively within the analyzed experimental domain, and extrapolating predictions beyond this scope is fraught with peril. Nonetheless, by identifying appropriate models, it is feasible to augment the impact response of composite structures. The influences of plate dimensions and the mass-velocity combination are investigated, as the critical parameter employed to characterize an impact is the kinetic energy of the impacting entity.

Experimental

Failure Criteria

The concept of failure in laminated composite materials can be categorized into three distinct classifications: the lamina failure criterion, the laminate failure criteria, and the criteria pertaining to structural failure. An examination of a lamina's failure criterion elucidates the various tensile states that precipitate failure. In the evaluation of laminate failure, a critical inquiry emerges regarding whether such failure is attributable to a singular lamina or necessitates the failure of all laminae. In the latter scenario, numerical analysis must incorporate the progressive failure of the laminas, thereby requiring the application of damage theory pertinent to the lamina.

The ultimate level of failure criterion is structural in nature. This criterion underscores the fulfillment of the structural objectives inherent in a specific project. It delineates an acceptable damage threshold for the engineered section. Among the most rudimentary failure theories are the maximum stress criteria and maximum strain [10]. Mominur Rahman [11] articulates that the maximum stress criterion was first posited by Ich-Long Ngo [12]. This criterion expands upon the maximum stress theory applicable to isotropic materials. According to this theoretical framework, the principal stresses contained within the material must remain below the allowable limits of strain corresponding to their respective loading directions.

Prevailing failure criteria conceptualize composite laminas as homogeneous and anisotropic, amalgamating diverse failure modes through a polynomial approximation. One of the most widely adopted general failure criteria is the quadratic failure criterion formulated by Tsai and Berdichevsky [13]. Other commonly employed generalized failure criteria encompass Hill, Tsai-Hill, and Hoffman. Nonetheless, the application and interpretation of the Tsai-Wu criterion unveil certain intrinsic challenges. The encapsulation of various failure modes within a singular function exhibits a lack of coherence. Anomalous expressions may arise, such as the allowance of faults with interdependent traction during biaxial compression loading. Furthermore, the characterization of the mode of material failure presents significant difficulties. This information is imperative for the incremental failure analysis of laminated materials. Hashin and Rotem [14], in conjunction with Hashin [15], proposed a novel set of failure criteria, which delineate distinct modes of material failure through individual equations. In this discourse, we propose a modification of this criterion for its application in bidirectional-laminated fabrics.

Hashin Failure Criterion Modified for Enhanced Laminas with a Bidirectional Woven Fiber

The methodology has been refined to facilitate a more precise evaluation of failure in laminas that are reinforced with bi-directional woven fibers. Given that the fibers are organized in dual orientations within this lamina, the failure modes associated with the fiber and matrix, as delineated by Hashin, are replaced with failure modes 1 and 2 corresponding to the orientation of the lamina. This updated failure criterion, designated as "Hashin modified" shall be utilized in the numerical simulations undertaken in the present investigation.

Failure Criteria of a Laminate

According to Hinton, Kaddour, and Soden [15], there exist four distinct parameters for evaluating the failure of a laminate when subjected to static loading conditions:

The onset of the initial failure within a lamina ("first ply failure"), The ultimate resistance prior to the complete failure of the laminate ("last ply failure"), The response in relation to strain, Supplementary qualitative considerations.

Irrespective of the selected laminate failure criterion, it is imperative to incorporate the material properties of the lamina, the expected loading scenarios, and the geometric variables such as the stacking arrangement and thicknesses of the laminate.

Structural Failure Criteria

As stated by Wu [10], a structural component is considered to have failed when it can no longer perform its intended function. Hinton and Soden [15] reveal that there is no widely accepted definition for what constitutes failure in a composite structure. Nonetheless, advancements in damage prediction allow for a more effective way to assess potential damage to the laminate structure throughout its lifespan or during production. By mastering the technology to more accurately measure intra-laminar damage or inter-laminar failure caused by various loads (such as impact, fatigue, and other factors), a significant connection is established to the criteria for defining structural failure. Currently, there is no extensive numerical or analytical approach that is straightforward and capable of assessing the strength and damage tolerance of RPC laminate structures; any project involving this material necessitates considerable safety margins in numerical evaluations and/or relies on experimental data from prior tests [16-18]. In cases where a structural element is critical for user safety or when its performance is vital for the project's economic feasibility, it is essential or highly advised to conduct experimental tests on the component itself to validate its strength characteristics and damage tolerance. Establishing a criterion for structural failure in RPC laminated material components is crucial at the outset of a project [19, 22]. Selecting an unsuitable criterion for structural failure could lead to alterations during the product development process. Since existing numerical tools necessitate a significant safety margin, adopting a new structural failure criterion might necessitate revisiting or even restarting an extensive series of structural tests [23, 24].

Lamina Degradation Criteria

In numerical analysis, it has been observed that after a lamina fails, one can determine which property is affected by examining the degradation laws. Mathews [10] notes that, as of now, there is no consensus on the properties and stiffness reduction factors to apply once a lamina has failed. A preliminary degradation model, known as D01, presumes that each failure mode leads to the total degradation of the modulus of elasticity in the respective loading direction.

A second model, referred to as D02, incorporates the reduction of the modulus of elasticity in direction 2 and the decline of the Poisson's ratio as this mode of failure occurs. Another plausible assumption involves diminishing the modulus of elasticity in direction 2 when a tensile failure takes place in direction 1. This form of degradation is anticipated particularly in more unidirectional laminates (the degradation criterion D03). Meanwhile, the modes of failure in compression or traction in direction 1 also lead to a reduction in the modulus of elasticity in direction 2, which is described as the degradation model D04 [25].

Results and discussion

The objective of the test established in this research is more extensive. Besides identifying the cracks or failures in the plate, it aims to assess the contact forces and damaged regions on the plate subjected to varying energy levels.

The evidence includes square plates measuring 350 mm on each side. The plates were tested with layers of epoxy resin reinforced using carbon fiber, with thicknesses of 10, 20, and 30 layers (see Table 1). Each layer has a thickness of 2.1 mm.

Table 1. Thickness of the test plates.

Plate	Thickness
$[0.90]_{10}$	2.1 mm
$[0.90]_{20}$	4.2 mm
$[0.90]_{30}$	6.3 mm

The measurements of the cylinder and the tip of the impactor depicted in Figure 1, along with their masses, have been recorded in Table 2 and Table 3. Initially, experiments were performed to determine the energy threshold that resulted in damage to the plates comprising 10 to 30 layers. Following that, a test campaign was conducted using an impact energy that exceeded the threshold for damaging the board.

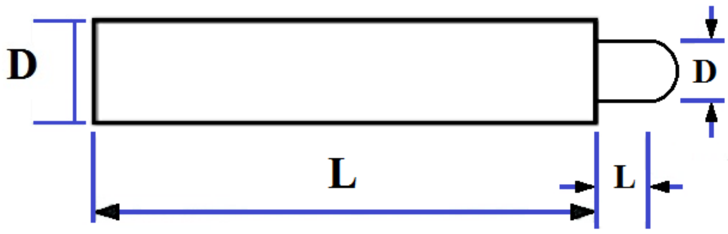

Figure 1. Dimensions of impactor test.

Table 2. Roller cylinder data.

Mass Nominal	Material	Mass (kg)	Lc (mm)	Dc (mm)
5	Steel	4.95	400	45.00
11	Steel	10.92	800	47.00

Table 3. Point impactor data.

Material	Mass (kg)	Lp (mm)	Dp (mm)
Steel	0.180	46.00	25.00

The findings from both numerical and experimental assessments of low-speed impact simulations are detailed and examined in this section. We begin by identifying the most suitable conditions for the numerical boundary and assessing the structural flexibility of each plate. The forces exerted on the impactor over time, both experimentally and numerically, are presented and compared. This initial phase involves a qualitative analysis of the force curves acting on an 11 kg impactor, utilizing two failure criteria (Maximum stress and Hashin Modified) and four distinct damage types (D01, D02, D03, and D04). To conduct a quantitative analysis of the numerical results, it was essential to evaluate the parameters that are influenced by these force curves.

The parameters analyzed included the force at damage initiation (Fth), the peak force during the event (F_{max}), the duration of the impact (T_{imp}), and the rebound energy of the impactor (E_r). Trend lines depicting these parameters in relation to impact energy have also been plotted for the analysis of the experimental findings. After this analysis, it was confirmed experimentally that the mass of the impactor has a minimal effect on the laminated plate's resistance to low-speed impacts. By establishing the mass of the impactor and the boundary conditions of the numerical model, the forces acting on the plate and the resulting damage were numerically obtained using various failure and damage criteria. These findings are presented and contrasted with the experimental data.

Comparisons with analytical results are also conducted for the upcoming energy level (E_{th}) of each plate.

In this study, the forces acting on the impactor are normalized based on the damage initiation forces (F_{th}) for each plate thickness, which were determined through experimental methods. These parameters are listed in Table 4. The lengths of the damage sustained and the areas affected are also normalized. This normalization was conducted relative to the extension values of damage (h_{ref} = 31 mm) and the damaged area (A_{dref} = 550 mm^2), both derived from the experimental impact test at 44 J with an 11 kg weight on the plate $[0.90]_{30}$. The experimental findings for impacts that resulted in no damage to the plates $[0.90]_{10}$ and $[0.90]_{30}$ are detailed in Table 5 and Table 6, respectively.

Table 4. Strength Values threshold of damage of the plates.

Plate	Experimental F_{th} (N)	Analytical Solution F_{th}- a (N)	Numerical Solution Maximum Tension F_{th}- n (N)	Numerical Solution Hashin Modified F_{th}- n (N)
$[0.90]_{10}$	2200	2018	2830	2820
$[0.90]_{20}$	5720	5708	6080	6080
$[0.90]_{30}$	11000	10486	11620	11620

Table 5. Experimental Measurements of Values Whose Impacts Caused no damage of the plate $[0.90]_{10}$.

CDP	m (kg)	V_i (m/s)	E_i (J)	F_{max}/ F_{th}	T_{imp} (ms)	$\Delta t_{F=0}$ (ms)
06-10	5	1.25	4.2	0.64	17.6	0.57
08-10	5	1.70	7.1	0.93	15.9	0.27
06-10	11	0.92	4.7	0.64	26.2	2.52
08-10	11	1.17	7.4	0.97	28.7	2.05

Evaluation of the Influence of the Mass of the Impactor

The findings illustrated in Tables 5 and 6 indicate the experimental impact energy levels that did not result in damage to the laminated boards when subjected to impactors weighing 5 kg and 11 kg, as summarized in Table 7. It was observed that delamination in the same board, under identical energy conditions, does not arise from variations in mass.

All experiments conducted with the 11 kg mass established a trend line correlating the damaged area (A_d) with the impact energy for each plate thickness. Figure 2 presents a comparison of these trend lines against the damage areas recorded for the 5 kg mass.

Table 6. Experimental Measurements of Values Whose Impacts Caused no damage of the plate $[0.90]_{30}$.

CDP	m (kg)	V_i (m/s)	E_i (J)	F_{max}/F_{th}	T_{imp} (ms)	$\Delta t_{F=0}$ (ms)
06-10	5	3.49	31.36	0.94	5.8	0.10
06-10	11	2.47	34.00	0.96	8.2	0.20

Table 7. Experimental Impact Energy Without the Occurrence of Delamination.

Plate	m (kg)	E_i (J)
$[0.90]_{10}$	5	4.1
	11	4.1
	5	7.2
	11	7.2
$[0.90]_{30}$	5	31.4
	11	34.0

From the analysis of the experimental damage areas (A_d), it can be inferred that impacts of equivalent energy, regardless of the mass used, result in comparable damage extents. Furthermore, the trend lines derived from the experimental data concerning (F_{max}) and (E_r) for the plate $[0.90]_{10}$, tested with the 11 kg mass, are juxtaposed with those obtained from the 5 kg weight in Figures 3 and 4, revealing a notable similarity in the results.

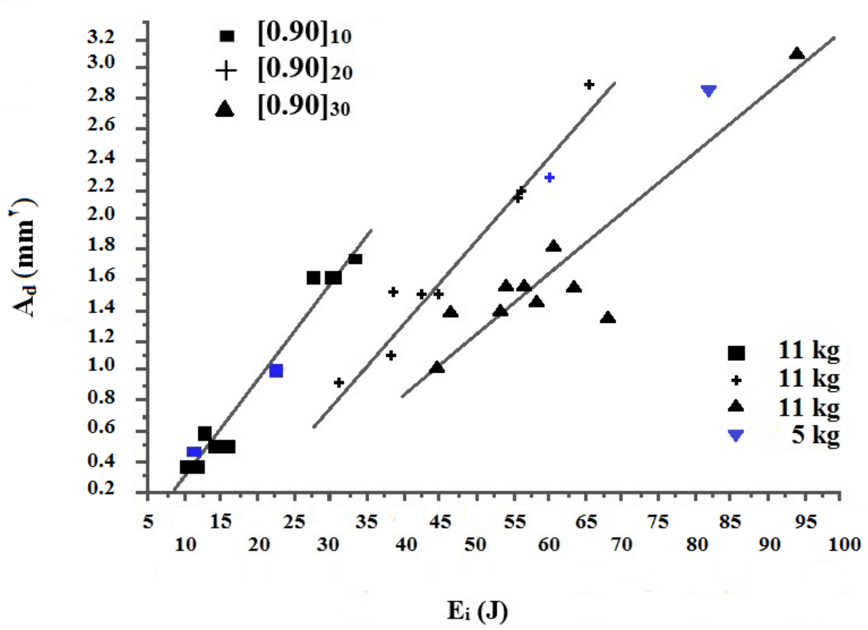

Figure 2. Comparison of experimental damage area with impactors of 5 (kg) and 11 (kg).

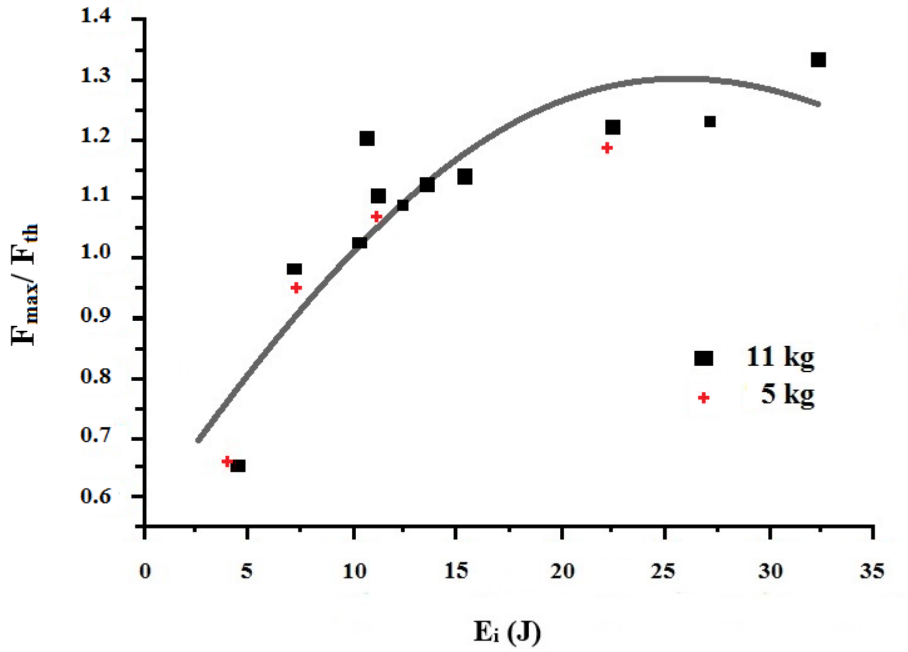

Figure 3. Comparison of (F_{max}) obtained experimentally with impactors of 5 (kg) and 11 (kg) on plate $[0.90]_{10}$.

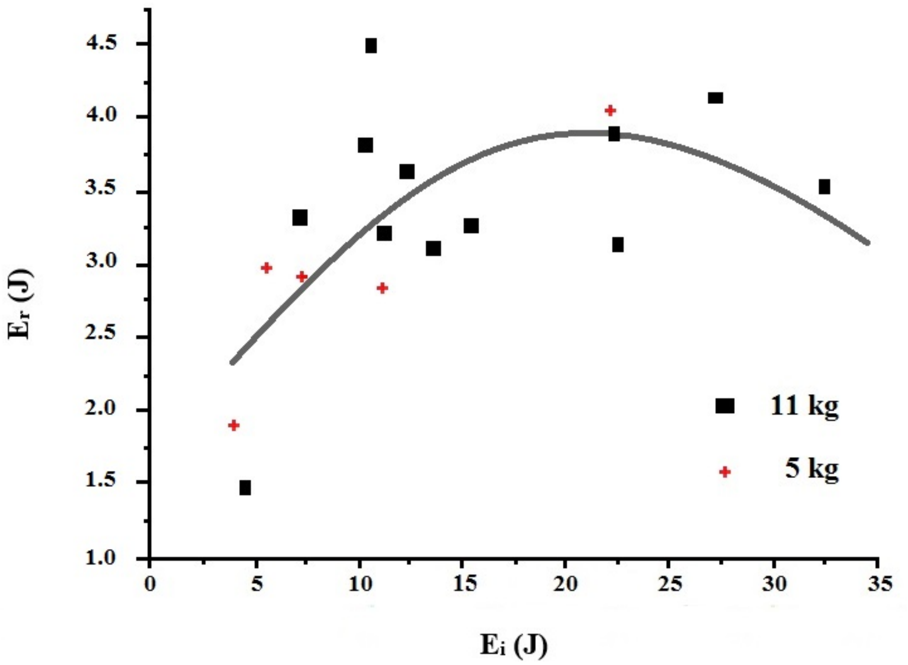

Figure 4. Comparison of (E_r) obtained experimentally with impactors of 5 (kg) and 11 (kg) on plate.

Impact Time

The impact times of specimens subjected to elevated impact energies (E_{th}) are illustrated in Figure 5. The linear trend lines corresponding to these experimental findings for each plate are depicted. Notably, it is evident that, for constant impact energy, the impact time diminishes as the plate thickness increases. This phenomenon can be attributed to the enhanced stiffness of the plate, which results in greater forces and accelerations. Conversely, an increase in impact energy correlates with a longer impact time, a relationship that can be attributed to the damage sustained by the plate. As damage occurs, the maximum force response of the plate is constrained to a threshold value (F_{th}), necessitating an extended impact duration for the impulse force to effectively return the impactor. Furthermore, as the threshold force (F_{th}) escalates with increasing plate thickness, the slope of the curves in Figure 5 exhibits a decreasing trend with greater thickness.

The numerical results for impact times appear to be consistent and reliable. The discrepancies between the numerical values of impact time (T_{imp}) and the experimental mean values are illustrated in Figures 6 through 8, where graphical comparisons are provided to highlight these differences.

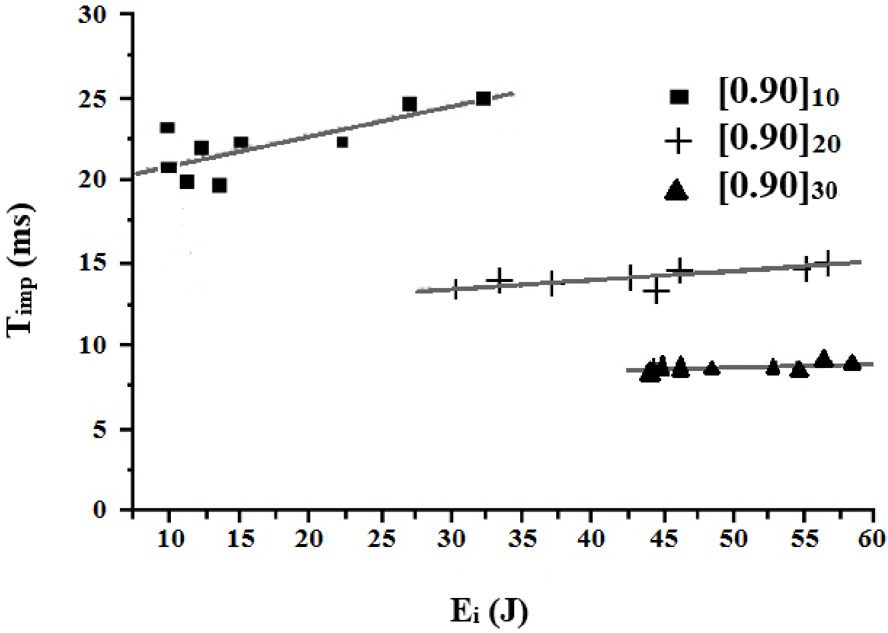

Figure 5. Impact time (T_{imp}) experimental with the impact m = 11 (kg).

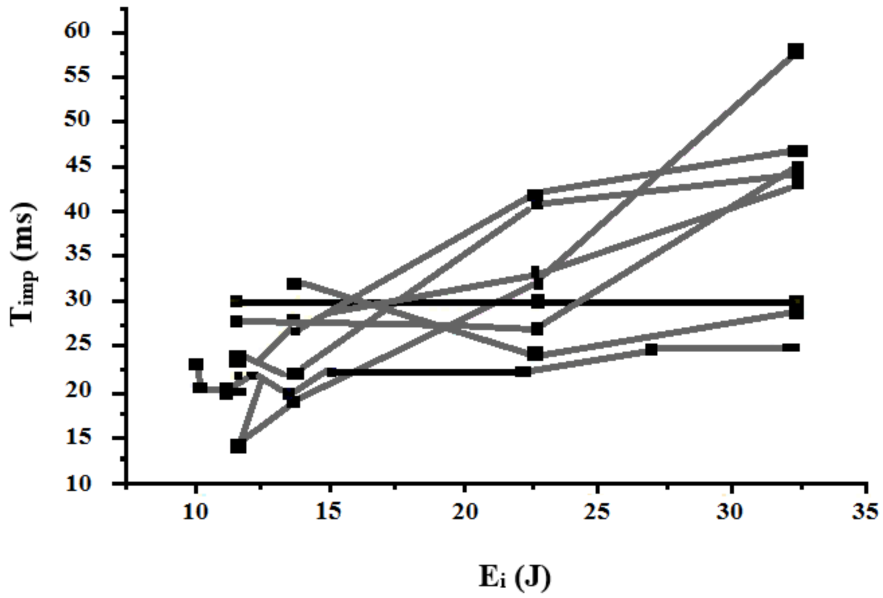

Figure 6. Comparison of time impact (T_{imp}) numerical and experimental, $[0.90]_{10}$.

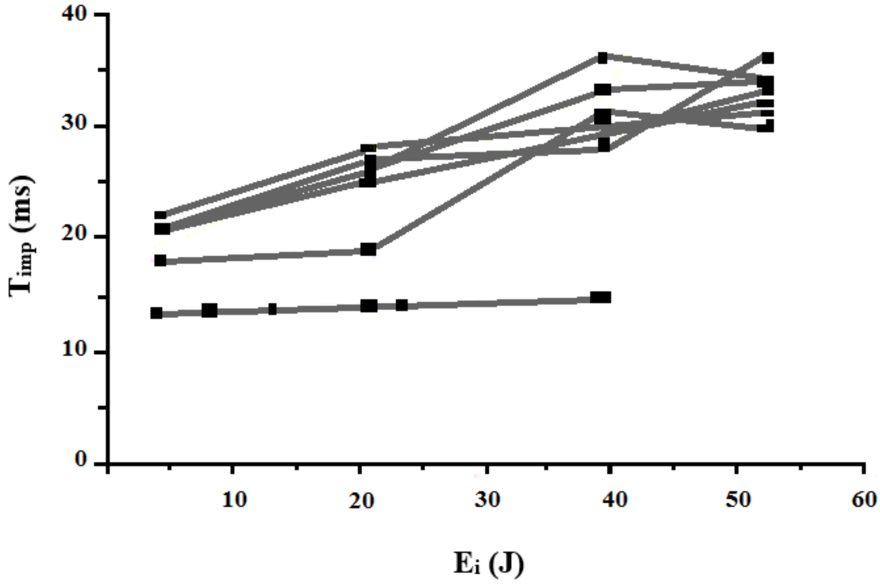

Figure 7. Comparison of time impact (T_{imp}) numerical and experimental, $[0.90]_{20}$.

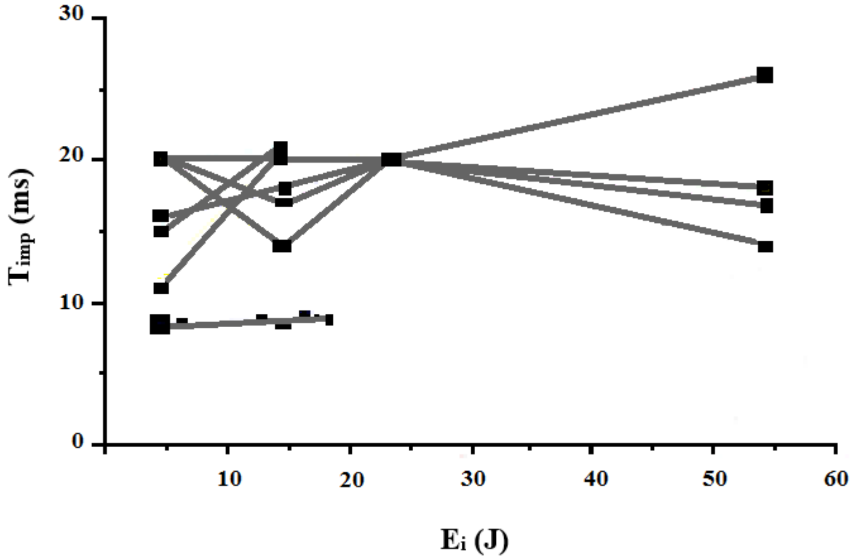

Figure 8. Comparison of time impact (T_{imp}) numerical and experimental, $[0.90]_{30}$.

Impactor Energy Return

The energy return of the impactor (E_r) refers to its kinetic energy at the conclusion of its interaction with the plate. This metric serves as a crucial parameter for assessing the accuracy of numerical simulations in relation to experimental outcomes. A strong correlation between the simulated and experimental values of (E_r) suggests that the temporal strength profiles of the curves are likely to align closely. In the experimental setup, the return speed of the impactor was determined by measuring the displacement at the moment of impact, which was calculated by deducting the initial displacement from the impulse force. The impulse force itself was derived by integrating the power over time using the trapezoidal rule within a spreadsheet framework.

Figure 9 illustrates the experimental findings of (E_r) when it exceeds the threshold energy (E_{th}). A trend line was established for the results corresponding to each plate, revealing that increased plate thickness correlates with a higher return energy of the impactor. This phenomenon can be attributed to the enhanced resistance of thicker plates to impact-induced damage. The data presented in Figure 9 further indicates that the return energy of the impactor stabilizes at a constant value, irrespective of the impact energy applied. Consequently, as the impact energy escalates, the energy loss of the impactor also increases, leading to a diminished energy return percentage (E_r /E_i), as depicted in Figure 10.

A comparative analysis of the return energies from both numerical simulations and experimental results is presented for each plate in Figures 11, 12, and 13. With the exception of the numerical simulation employing the Hashin Modified criteria on the plate $[0.90]_{10}$, the numerical solutions generally exhibited an increase in the impactor's energy return with rising impact energy. In contrast, the experimental value of (E_r) remained relatively constant, resulting in greater discrepancies in the (E_r) values as the impact energy increased. This divergence in return energy during experiments may be attributed to additional damage sustained by the plate or unaccounted losses due to friction and damping in the numerical models. Furthermore, it is plausible that the experimental plate experienced higher strain energy or greater kinetic energy of vibration at the conclusion of the contact period.

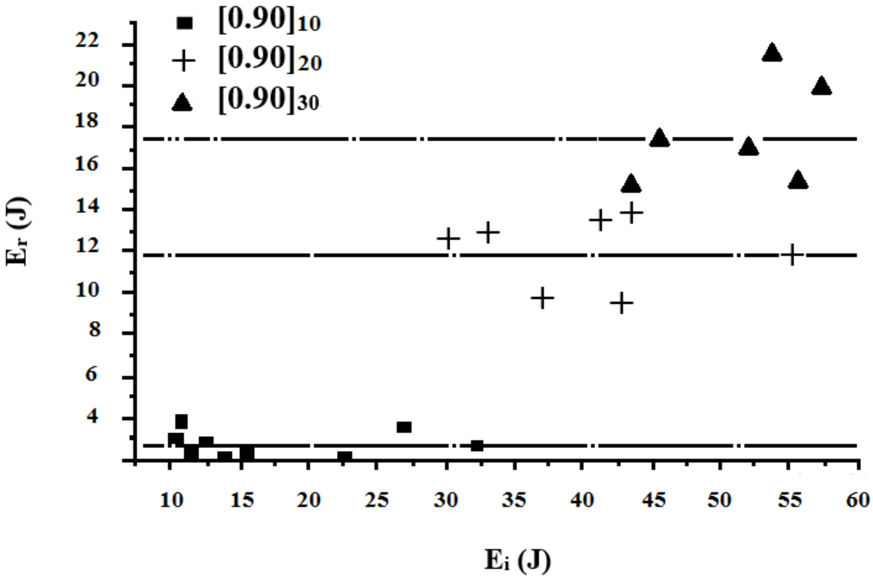

Figure 9. Experimental results of Energy return (E_r) by the impactor 11 (kg).

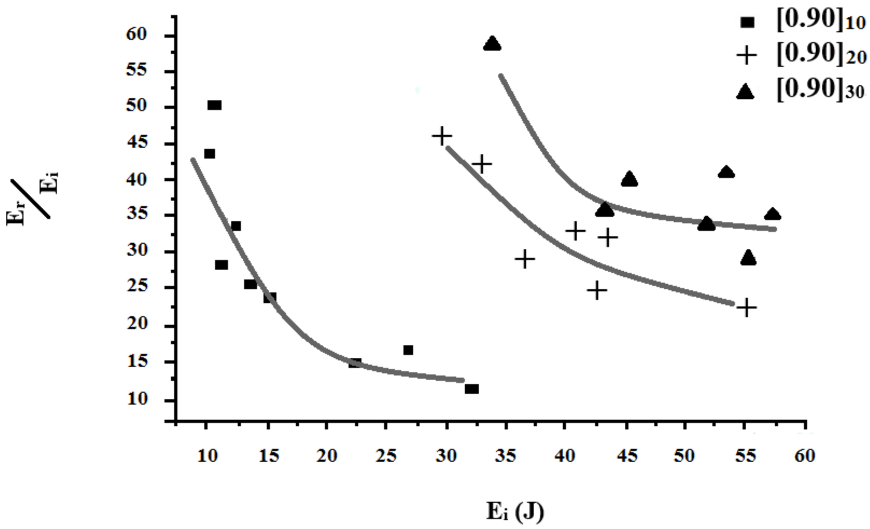

Figure 10. Experimental results of (E_r/E_i) by the impactor 11 (kg).

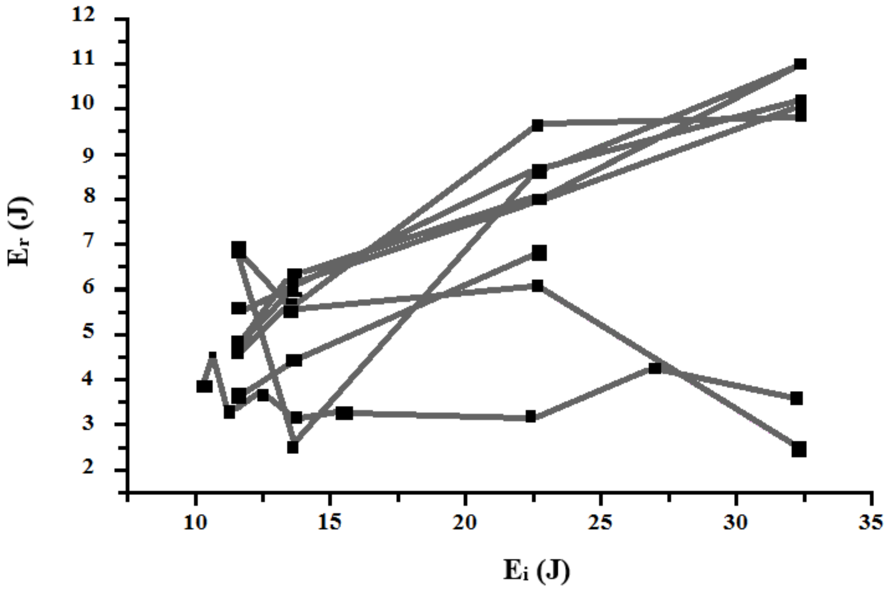

Figure 11. Return power comparison (E_r) numerical and experimental, $[0.90]_{10}$.

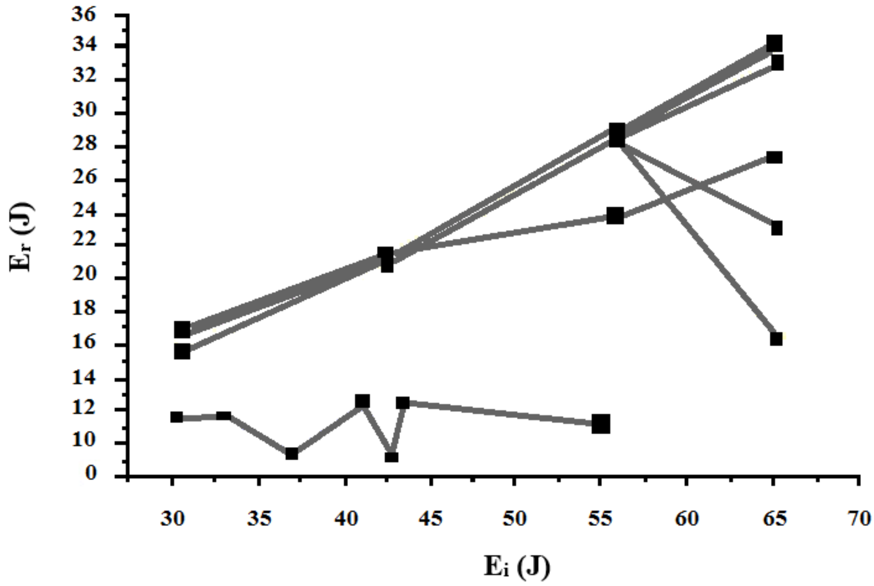

Figure 12. Return power comparison (E_r) numerical and experimental, $[0.90]_{20}$.

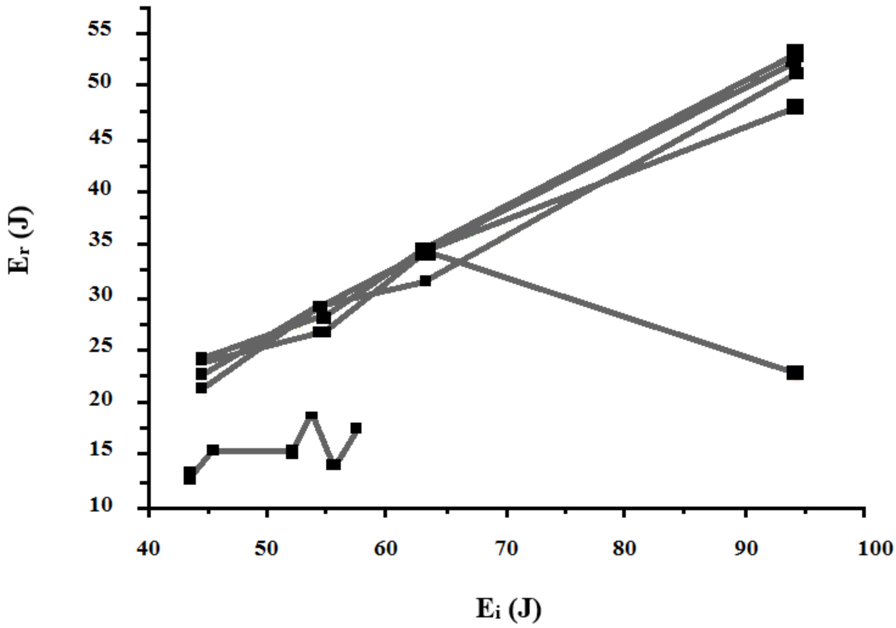

Figure 13. Return power comparison (E_r) numerical and experimental, $[0.90]_{30}$.

Conclusion

This research indicates that numerical models designed to capture the structural integrity of laminated materials often face challenges in accurately depicting their non-linear behavior and the intricate failure mechanisms associated with both the plate and the laminate. A numerical approach developed to assess the damage resistance of laminated plates, specifically those reinforced with bidirectional woven carbon fiber and epoxy resin, yielded promising outcomes. Nonetheless, this method also encountered certain limitations regarding its practical applicability.

The selection of an appropriate failure criterion and degradation model is contingent upon the thickness of the laminated plate and the specific impact energy levels intended for evaluation. Notably, the failure criterion derived from Hashin's theory, coupled with the degradation model identified as D02, emerged as a versatile numerical framework applicable across various plate thicknesses and energy levels examined in this research. The temporal analysis of contact forces between the impactor and the plate produced satisfactory results, with some instances demonstrating exceptional performance.

Caution is advised against extrapolating the findings, as the failure modes of laminated materials can vary significantly. It is recommended that future investigations focus on the analysis of failure criteria and degradation mechanisms across different stacking sequences and a broader range of impact energy levels. Such studies could enhance the understanding of the behavior of laminated materials under diverse conditions and contribute to the refinement of numerical modeling techniques.

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