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Proceeding Paper

Experimental and Numerical Investigation on Damage Resistance Characteristics of Woven E-Glass/Epoxy Composite Laminates Subjected to Drop-Weight Impacts †

Ranjith K. [1,*], Prithvi C. [2], Rajesh Mathivanan N. [3] and Rakshith Gowda D. S. [1]

1 Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysuru 570002, Karnataka, India; rakshithgowda@vvce.ac.in
2 Department of Mechanical Engineering, The National Institute of Engineering, Mysuru 570008, Karnataka, India; prithvi.mech@nie.ac.in
3 Department of Mechanical Engineering, PES University, Bengaluru 560085, Karnataka, India
* Correspondence: ranjithraj@vvce.ac.in; Tel.: +91-8073290872
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Abstract: The utilization of composite materials in structural components has been on the rise in the aerospace, automotive, and marine industries. Although these materials offer numerous benefits, they can be damaged by various sources, such as low-velocity drop-weight impacts. Debris on a runway or tools falling onto composites can cause this type of impact, which has led to extensive research on crashworthiness and impact damage assessment. This study aimed to assess the response of woven E-glass/epoxy composite laminates under low-velocity drop-weight impacts. Tests were conducted using experimental methods and numerical simulations with a drop-weight impact-testing machine and the explicit finite element software LS-DYNA. The experimental tests were performed according to ASTM standards, with varied magnitudes of initial impact energy ranging from 7.85 J to 23.54 J and a specimen thickness of 4 mm. Force–time, energy–time, and force–displacement histories, obtained through the experiments and numerical analyses along with images of the damaged specimens, were examined. The effective stress contours are also illustrated to gain a deeper comprehension of the stress distribution in the laminates. The findings demonstrated that the impact energy significantly influences the impact response of the specimens, and both the experimental and numerical analyses yielded similar results, validating the modeling approach for the impact problem in composite materials. The study provides insight into the damage mechanism of woven E-glass/epoxy composite laminates under drop-weight impacts and is expected to contribute to a better understanding of their response in low-velocity drop-weight impact events.

Keywords: drop-weight impact; LS-DYNA; damage resistance; E-glass/epoxy

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1. Introduction

Drop-weight impact damage could significantly diminish the strength and structural integrity of composite materials. This damage may not be detected sometimes by visual inspection. Such impact-induced damages occur inside the composite material and increase after the onset of minor delamination. Consequently, the impact behavior of laminated composite materials is an important phenomenon to be studied. Woven-fabric composites have superior impact resistance due to the interlacing of fiber tows in two directions. They also exhibit high toughness, better damage tolerance, are easy to manufacture, and maintain their shape consistently under varying temperature conditions [1]. Many studies have examined how composite laminates respond under impact loading. Delamination and fiber breaking were found to be the main damage modes for woven laminates in a study on carbon epoxy composite plates' responses to low-velocity impacts [2]. An investigation on rectangular, hand-laminated woven roving E-glass polyester composite plates with different thicknesses revealed multiple, complex, and interacting damage mechanisms, even with impacts of very low energy [3]. The finite element analysis technique was used to evaluate the failure of thin composite laminates in the event of low-velocity impacts using a user subroutine in the ABAQUS software [4]. Unidirectional and woven composite laminates respond to low-velocity impact loading, and when the specimen absorbs low levels of energy, the impactor tends to rebound [5]. Laminates made from single-ply 3D orthogonal woven fabric have superior energy absorption and impact damage resistance compared to those made from unidirectional and 2D plain-woven fabric [6]. To accurately model the impact behavior of carbon fabric composite laminates in DYNA3D using energy-based damage mechanics, it is necessary to compare with experimental data at the coupon level [7]. Creating appropriate laws to represent the failure of composite laminates and material models with finite element codes for an impact event can greatly aid in designing specific structures [8]. The damage initiation of composite laminates was modeled in Abaqus/Explicit, using the three-dimensional Hashin failure criterion [9]. A newly developed three-dimensional finite element model was effectively used for the analysis of compression-after-impact properties of composite laminates [10]. The analysis of interlaminar damage responses in CCF300/epoxy composite laminates was conducted using a cohesive contact formulation [11]. A radiology-based technique was adopted in measuring the delaminated area of carbon/epoxy composite laminates under a low-velocity impact event [12]. The finite element model was unable to accurately predict intricate responses, such as shear plugging and extreme delamination in thermoplastic composites reinforced with non-crimp carbon fiber-based fabric [13]. Better impact resistance was observed in laminates that had a higher areal density and more layers of nickel-coated carbon fiber veils, which resulted in a higher impact force and smaller damage area [14]. The shape of the impactor has a considerable effect on the extent of damage induced in composite laminates during impacts at low velocity [15]. A considerable reduction in computational costs was achieved by implementing the mass-scaling method in the numerical analysis of the impact response of semicylindrical woven composite shells [16]. In the past, impact damage models relied on either analytical calculations or extensive experimental data. However, analytical predictions have been proven to be unreliable and overly simplistic. On the other hand, conducting practical tests for every design is expensive, time-consuming, and complex. As a result, low-cost virtual testing using numerical simulations is becoming increasingly important in engineering development. Validated simulations can help analyze the damage progression in the laminate during an impact event and conduct efficient parameter studies for geometries, laminate configurations, and loading conditions. The main goal of this work is to study the response of woven fabric E-glass/epoxy composite laminates to low-velocity impacts through a proper assessment of force–time, energy–time, and force–displacement histories, as well as the damage modes obtained from experimental testing, plus numerical simulations.

2. Materials and Methods

2.1. Materials and Specimen Fabrication

The specimens used in this study were made from E-glass fabric with a plain weave and an areal weight of 360 g/m^2. To create the composite panels, a Lapox L-12 resin and K-5 hardener epoxy matrix was chosen, with a glass fiber volume fraction of approximately 63%. The panels were made through a hand layup process and had a stacking sequence of $[0/90]_9$, with a thickness of 4 mm. They were initially cured for 12 h at room temperature under a constant pressure of 0.2 MPa using a hydraulic press. Later, the laminates underwent post-curing at 120 °C for 4 h, followed by cooling to the surrounding room temperature. The required test specimens were cut from the composite laminates to have an in-plane dimension of 150 mm × 150 mm.

2.2. Low-Velocity Drop-Weight Impact Test

Figure 1a displays an instrumented drop-weight impact test machine. This machine was employed to perform impact tests on the composite panels. The machine is equipped with an adjustable crosshead, a weight assembly, an impactor, a piezoelectric load cell, a velocity sensor, and an accelerometer. Data acquisition was accomplished by collecting and storing signals from the load cell, which were then converted into impact characteristics, including the contact force, energy absorbed, and displacement. Additionally, two steel guide rails were employed to ensure the smooth delivery of the weight onto the laminates, and a steel fixture was utilized to clamp the specimens, as illustrated in Figure 1b.

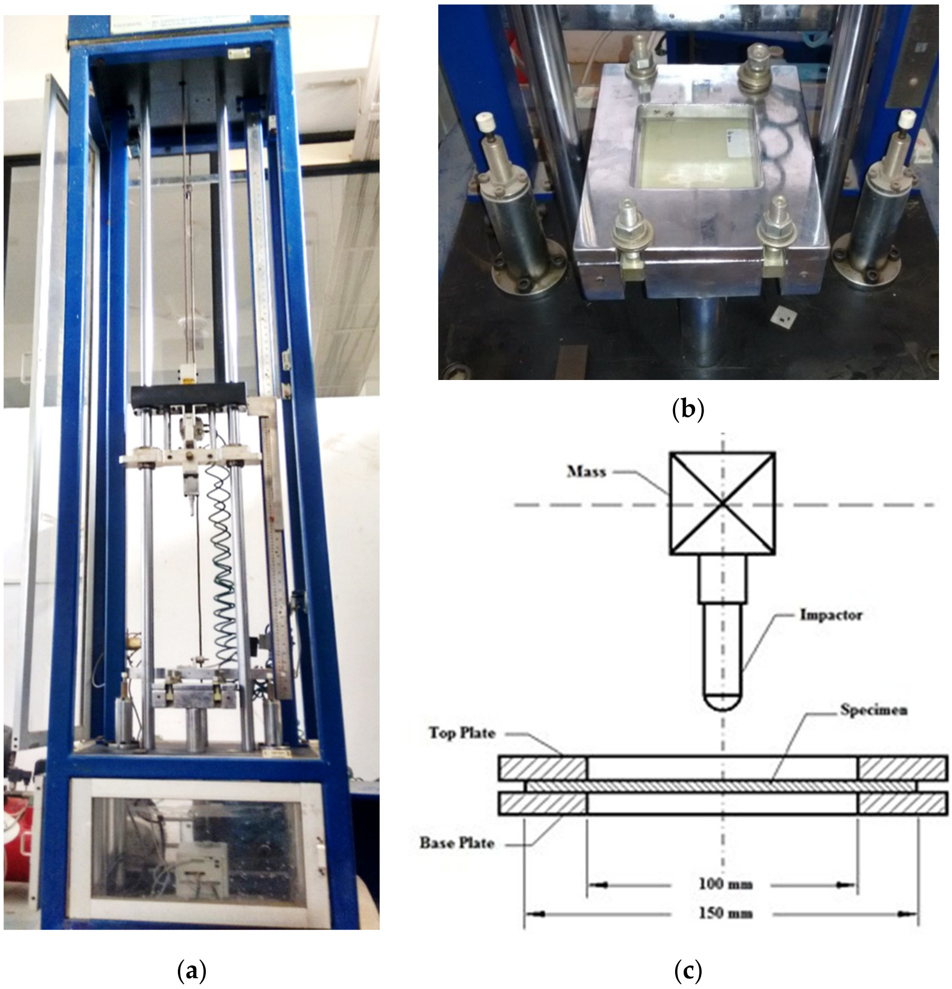


Figure 1. Experimental test setup: (**a**) drop-weight impact test machine; (**b**) fixture arrangement to clamp the specimen; (**c**) schematic of the drop-weight impact test.

The test was conducted as per the latest ASTM standard, D7136. This method is commonly used to measure the damage resistance of polymer matrix composites when subjected to impacts from a drop weight [17]. A hemispherical-headed tup with a diameter of 10 mm was attached to the lower end of the piezoelectric load cell. The stainless-steel impactor was assumed to be perfectly rigid. Composite laminates with dimensions of 150 mm × 150 mm × 4 mm were considered for the present work. The laminates were clamped onto the fixture, consisting of a base plate and a top plate with a 100 mm × 100 mm slot located straight under the impactor, as shown in Figure 1c. The impact point is located in the center of the plate. A constant clamping force on all edges of the laminate was ensured using pre-loaded helical springs. The weight of the drop weight was fixed at 1.6 kg for all the test cases, and the impactor was dropped from different heights of 0.5 m, 1 m, and 1.5 m. Vertical guide rails were lubricated frequently to minimize the friction generated during the descent of the impactor.

2.3. Numerical Simulation

The simulation of the drop-weight impacts on the woven E-glass fiber/epoxy composite laminates was carried out using the software LS-DYNA® [18]. The model has two parts: a plate and an impactor with a hemispherical tip, as illustrated in Figure 2. The plate, with an in-plane dimension of 150 mm × 150 mm and a thickness of 4 mm, was modeled using 784 deformable two-dimensional 4-node thin-shell elements. The impactor, with a hemispherical tip having a radius of 5 mm, was treated as a rigid body and meshed using 1860 solid elements with 8 nodes. The layup and thickness of the plies, the material direction of each element, and their element formulation were defined through a property called PART_COMPOSITE.

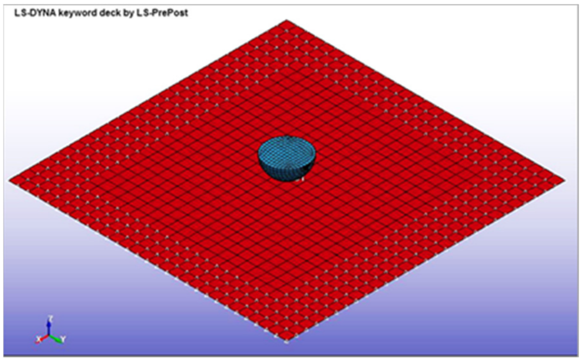


Figure 2. Impact test model in LS-PrePost.

2.4. Material Model and Failure Criteria

The simulated material behavior is governed by the material model. A material model named MAT_RIGID was used for the hemispherical impactor. MAT 54 or the MAT_ENHANCED_COMPOSITE_DAMAGE material model was adopted to predict the behavior of the orthotropic composite material. MAT 54 uses an orthotropic elastic stress–strain relation established based on the full Chang–Chang criterion, which is formulated as a separate criterion for four different modes of failure [19]. The properties of the plain-weave E-glass/epoxy composite laminate are summarized in Table 1.

Table 1. Properties of plain-weave E-glass/epoxy composite laminate [20].

Property	Unit	Value
Density (σ)	Kg/m^3	1808
Longitudinal Young's Modulus (E_{11})	GPa	20.8
Transverse Young's modulus (E_{22})	GPa	20.8
Shear modulus (G_{12})	GPa	3.92
Minor Poisson ratio (ν_{21})	-	0.173
Longitudinal Tensile strength (X_T)	MPa	250
Longitudinal Compressive strength (X_C)	MPa	183
Transverse Tensile strength (Y_T)	MPa	250
Transverse Compressive strength (Y_C)	MPa	183

The initial condition includes assigning an initial velocity to the impactor. The input velocities for the analyses were obtained from the experiment. The boundary conditions included defining constraints, contacts, etc.; in this case, the composite laminate was clamped along all four sides. Therefore, some nodes along the four edges of the laminate were fixed in all directions (x, y, z) to simulate the experimental clamped conditions. The impactor was constrained to move only in the direction (z) normal to the laminate.

The contact of the impactor with the composite laminate was defined using the AUTOMATIC_SURFACE_TO_SURFACE contact algorithm.

3. Results

Several experimental tests were conducted for varied drop heights corresponding to an impact velocity range of 3.132 to 5.425 m/s. The calculated impact energy ranged from 7.85 J to 23.54 J. Numerical simulations of the tests were accomplished using the LS-DYNA software. The results from the experimental tests and numerical simulations are summarized in Tables 2 and 3, respectively.

Table 2. Summary of experimental test results.

Specimen Code	Height of Fall (m)	Impact Velocity (m/s)	Impact Energy (J)	Max. Force (N)	Absorbed Energy (J)	Displacement at Max. Force (mm)
1	0.5	3.132	7.85	2355	6.4	10.23
2	1	4.429	15.70	3582	13.41	15.02
3	1.5	5.425	23.54	4387	22.15	16.41

Table 3. Summary of numerical simulation results.

Specimen Code	Height of Fall (m)	Impact Velocity (m/s)	Impact Energy (J)	Max. Force (N)	Absorbed Energy (J)	Displacement at Max. Force (mm)
1	0.5	3.132	7.85	2314	6.71	10.1
2	1	4.429	15.70	3505	13.68	14.25
3	1.5	5.425	23.54	4263	21.62	15.53

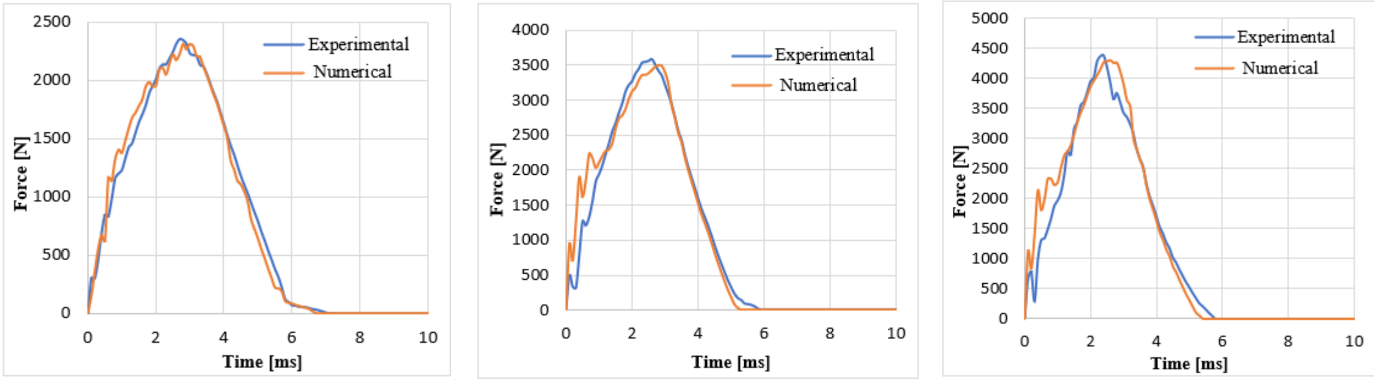
4. Discussions

4.1. Force–Time History

During the experiment, the load cell measured the contact force directly, while the RCFORC output file in LS-DYNA was used to determine the reaction forces. Figure 3 shows a comparison of the force–time (F-t) histories for impact energy levels of 7.85 J, 15.7 J, and 23.54 J. The force–time history provides important information about the initiation and growth of damage in the laminates. When the energy of impact is low (7.85 J), the F-t history shows a symmetric parabolic-shaped curve, indicating that there is almost no significant damage during the contact. However, when the energy increases, the contact force also increases, leading to major damage inside the laminates. The force reaches a peak before dropping, owing to the impactor rebound. The presence of oscillations in the curves indicates the progression of damage.

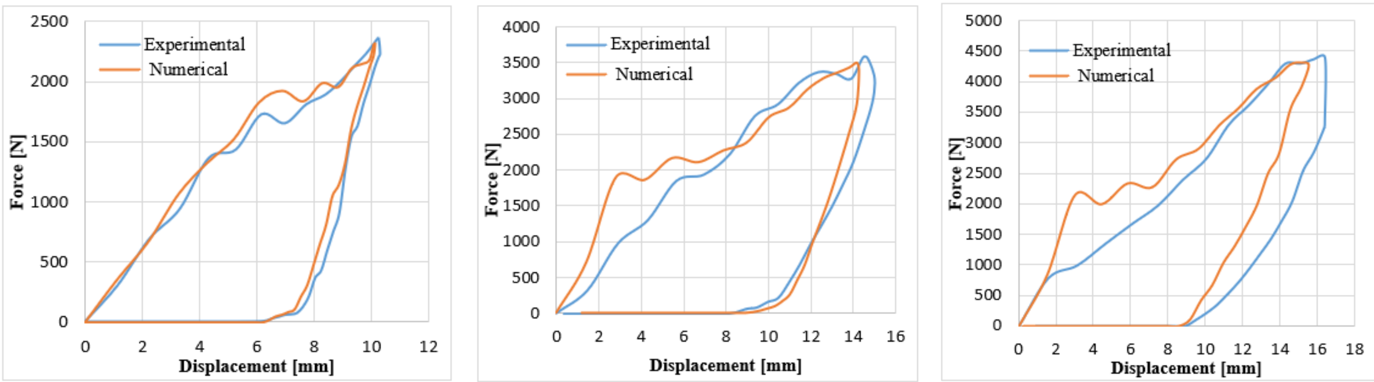
4.2. Force–Displacement Curves

These curves contain essential information about the damage progression under impact. Figure 4 compares the experimental and numerically predicted force–displacement curves for the woven glass/epoxy composite laminates for varying magnitudes of impact energy. As the energy increases, the load reaches a maximum level. Beyond that, it descends until rebounding occurs, resulting in complete or partial rebounding. The area beneath the curve indicates the amount of energy that is transmitted to the laminate progressively, before being returned to the impactor during the rebound process. The area enclosed within the loop denotes the energy that the laminate has permanently absorbed during the impact. For small impact energy (7.85 J), the closed-form curve is insignificant, indicating less damage to the laminate. The rebounding component becomes progressively smaller as the energy level increases, meaning that the laminate absorbs more energy due to damage.



(**a**) (**b**) (**c**)

Figure 3. Force–time curves at impact energies: (**a**) 7.85 J, (**b**) 15.70 J, (**c**) 23.54 J.



(**a**) (**b**) (**c**)

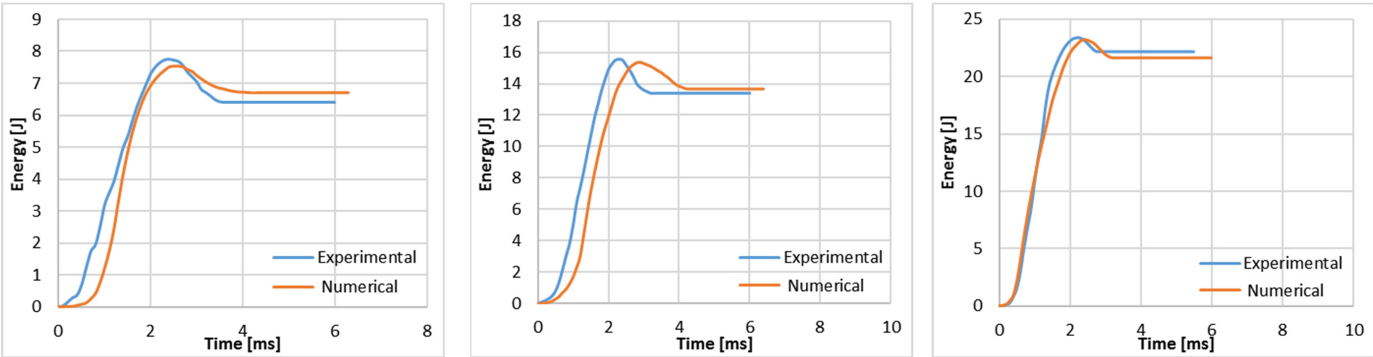
Figure 4. Force–displacement curves at impact energies: (**a**) 7.85 J, (**b**) 15.70 J, (**c**) 23.54 J.

4.3. Energy–Time Curves

Figure 5 presents the energy–time histories for impact energies ranging from 7.85 J to 23.54 J. The curves in the figure show that during loading, each curve increases with time, reaches a maximum value, and then decreases during unloading and finally remains horizontal. The constant value at the end of each curve represents the total energy that the laminate has permanently absorbed due to damage during the impact. Different failure mechanisms, such as matrix crack, delamination, and fiber breakage, absorb some of this energy. The maximum value of each curve represents the associated impact energies. The difference between the maximum and constant value is referred to as rebound energy, which is the elastic energy stored by the laminate and transmitted to the impactor, causing it to rebound in the case of non-perforated laminates.

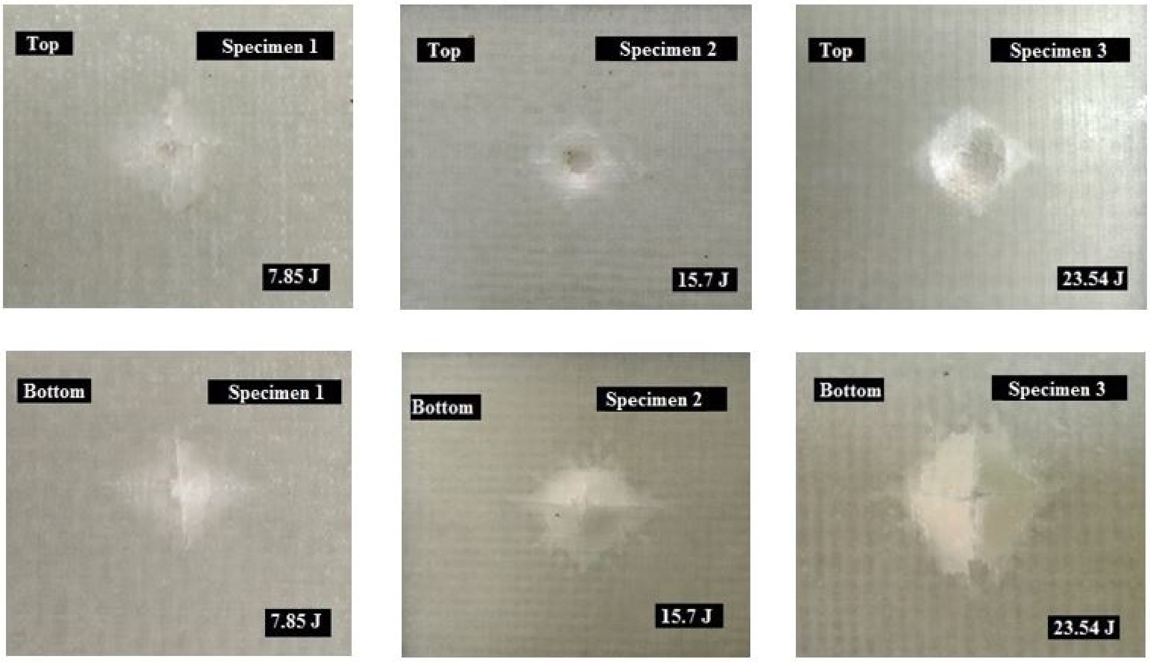
4.4. Damage Analysis

The specimens were visually inspected to determine how the test conditions influenced the degree of the damage. For a better view, close-up images of the top (impacted) and bottom (non-impacted) faces were captured and can be seen in Figure 6. In the case of specimen 1, under a low level of impact energy (7.85 J), there was a small dent on the top face and matrix cracks on both faces, as exhibited in Figure 6a. However, specimens 2 and 3, which were exposed to an increased level of impact energy (15.7 J and 23.54 J), showed a small amount of penetration with a more significant dent on the top surface, and the non-impacted surface had a slight splitting in the fill and warp directions, as seen in Figure 6b,c. In all cases, the visible delaminated area had a diamond shape, with the principal axes aligning with the warp–weft directions of the fabric layers (horizontal and vertical directions in the figures).



(**a**) (**b**) (**c**)

Figure 5. Energy–time curves at impact energies: (**a**) 7.85 J, (**b**) 15.70 J, (**c**) 23.54 J.



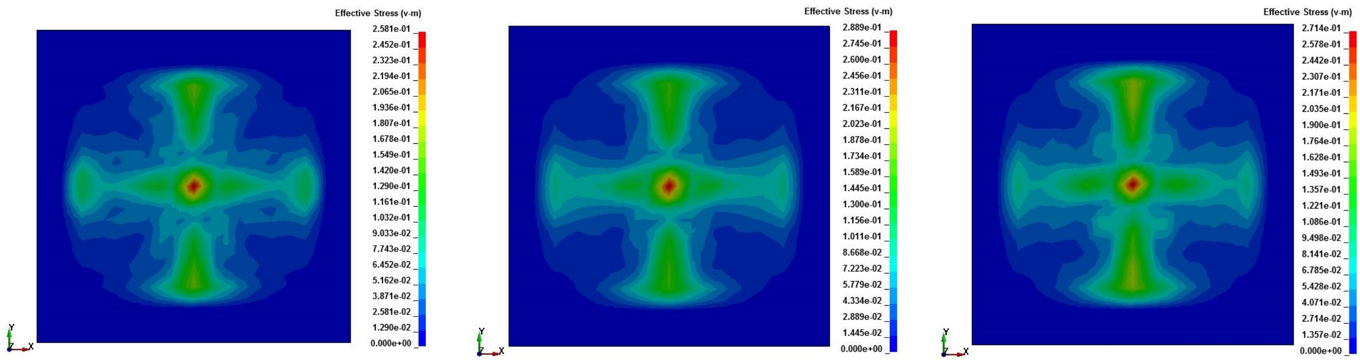
(**a**) (**b**) (**c**)

Figure 6. The top and bottom surfaces of the laminates at impact energies: (**a**) 7.85 J, (**b**) 15.7 J, (**c**) 23.54 J.

The contours of effective stress (von Mises) reveal that when the impactor contacts the surface of the laminate, the stress waves spread along the warp and weft directions, as seen in Figure 7a–c. A symmetric distribution of stress is observed under fully clamped conditions at all the edges. This can be attributed to the symmetric boundary conditions of the laminate. Furthermore, it is observed that the primary yarns in the both warp and weft directions experience higher stress levels compared to the secondary yarns. Also, the maximum stress is developed at the middle of the laminate, owing to the applied impact load.

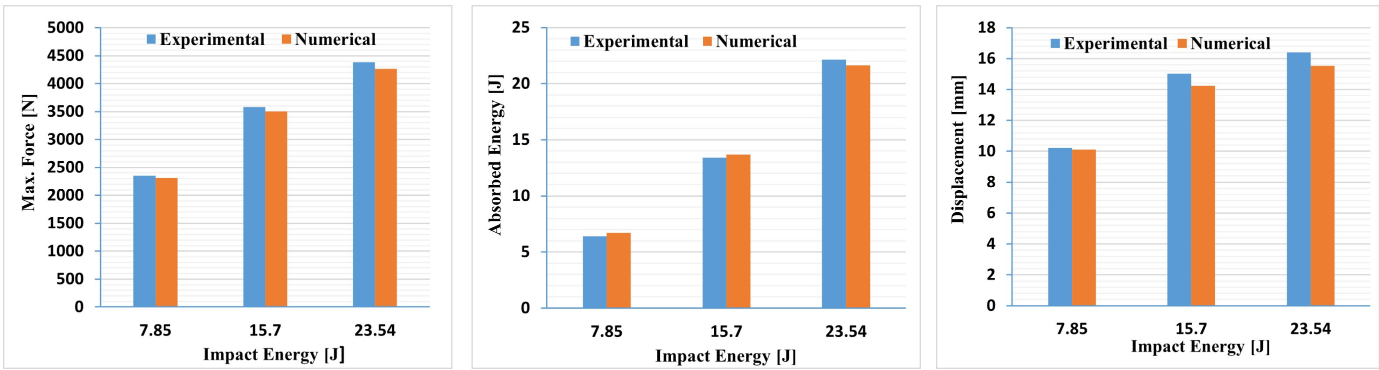
4.5. Effect of Impact Energy on Damage Resistance Characteristics

This discussion explores how the impact energy affects major impact parameters such as the maximum force, energy absorbed, and impactor displacement at maximum force. Figure 8a–c illustrate the results of the impact tests conducted at different levels of impact energy for the above parameters. The graph for maximum force versus impact energy shows that the higher the energy level, the higher the maximum force. Additionally, the graphs reveal that impactor displacement increases with higher impact energy values. The absorbed energies represent a fraction of the impact energy that the structure absorbs and does not convert into elastic energy. It is evident that as the energy level increases, the extent of damage also increases, leading to higher absorbed energy values. Furthermore, both the experimental and numerical results reveal similar trends.



(**a**) (**b**) (**c**)

Figure 7. Contours of effective stress at impact energies: (**a**) 7.85 J, (**b**) 15.7 J, (**c**) 23.54 J.



(**a**) (**b**) (**c**)

Figure 8. Effect of impact energy on (**a**) maximum force, (**b**) absorbed energy, and (**c**) impactor displacement at maximum force.

5. Conclusions

The damage resistance characteristics of woven E-glass/epoxy composite laminates were analyzed using practical tests and simulations to study their behavior under drop-weight impacts. The numerical simulation approach used to predict the maximum force, energy absorbed, and displacement at maximum force showed good agreement with the experimental results. The response of the woven glass/epoxy composite laminates to drop-weight impacts is sensitive to the energy level of the impact. As the incident impact energy level increases, the maximum force, absorbed energy, and impactor displacement at maximum force also increase. A visual inspection of the damaged specimens revealed various failure modes of the woven glass/epoxy composite laminates, including permanent indentation on the impact face, matrix crack, delamination, fiber damage, and penetration, depending on the impact energy level.

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