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EXPLORING DELAMINATION PATTERNS IN DYNEEMA COMPOSITE LAMINATES UNDER HIGH-VELOCITY IMPACT: AN LS-DYNA SIMULATION INVESTIGATION

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Abstract

Failure of composite not only includes tensile or compression failure of fiber matrix, but also the delamination between plies. The current study investigates a methodology for the Ply-Delamination of Dyneema material due Ballistics impact using LS-DYNA. A new methodology was implemented in order to effectively capture the ply delamination and the damage caused due to the impact for different velocities. Numerical results obtained were correlated with previous existing simulation results.

Keywords: Composite delamination, Dyneema, Explicit analysis, Impact Dynamics, Ls-Dyna, *MAT_59.

1. INTRODUCTION

Composite materials play a vital role in the present day engineering design and development activities due to their attractive mechanical properties and are classified as laminated, FRP and MMC's. Laminated composites are more popular in aircraft structures and components made form laminated composites are installed in aircrafts to absorb energy during risk/damage to critical machine components. It is noticed that energy-absorbing shields are employed in a variety of industries, including energy, automobile, rail, aviation, mining, and maritime transportation among these aviation and military industries have the highest demands. Depending on the use, composite shields are exposed to different types of loads from small stones/pebbles, hail stones, birds, gunfire, or explosive debris. Use of the shields in aircraft helps to reduce the damage to other load bearing members.

In the current research work, a new material Dyneema® made of UHMWPE is light weight, high modulus and superior strength and 15 times stronger than steel and 40% stronger than aramid fibers are made using a proprietary gel spinning process which involves drawing, heating, extruding, and cooling the fibers. Stretching and spinning in a controlled manner produces molecular re-alignment, resulting in high crystallization and low density Dyneema fibers makes an ideal choice for Aerospace and Military applications.

These fibers are subjected to different types of failure like fiber breakage, matrix cracking, delamination etc, delamination is common in FRP and laminated composites which affects the strength, stiffness, and resistance to buckling of a structure's. Delamination, indicating interlaminar failure, and matrix cracking, signifying intralaminar failure, arise from inadequate bonding within the lamina/laminate of composites **(Figure: 1)**. ultimately, these defects contribute to a total structural failure.

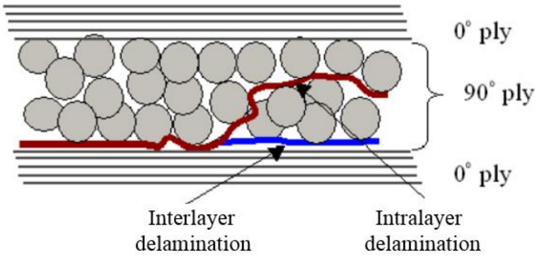

Figure 1: Delamination and matrix cracking in laminated composite [6]

Consequently, numerous researchers have endeavored to examine the behavior of delamination and damage in plies through a combination of numerical simulations and experimental approaches. An effort has been made to understand the previous methodology and a detailed analysis. **Sagar et al. [2]** employed experimental data to anticipate delamination and in-plane damage, assessing the efficacy of their modeling technique through diverse analyses and modeling software, including FE code and LS-DYNA. The stacked shell element approach proves most advantageous when a potential delamination interface can be anticipated. It is evident from the results that the projected force-time outcome closely matched with the experimental results, and the predicted damage area not deviated by more than 20% from the experimental results. **Bazle et al. [3]** conducted experiments on a thick-section laminate made of plain weave S-2 glass/SC15 epoxy composite under quasi-static punch shear loading to investigate delamination behavior. The experimental findings were subsequently compared with LS-DYNA simulations utilizing MAT 162 as the material model. The results clearly demonstrate a strong agreement between the experimental and simulated results. Additionally, the study incorporated the use of the TIE-BREAK interface option to model delamination behavior of the composites. **Robin Olsson et al. [4]** examined a delamination of transversely isotropic laminated plates subjected to high-velocity impact and possessing small mass. It is evident from the results that estimated delamination threshold loads and velocities are correlate well with the FEA models when the plate thicknesses are in the range from 2 to 6 mm. **Esteban et al. [5]** investigated the application of LS-DYNA for modeling procedures tailored to graphite/epoxy composite materials, specifically focusing on analyzing interlaminar and delamination failures through diverse approaches. The results indicate that the efficiency achieved with the proposed model marks progress in advancing the realistic simulation of mesoscale models for composite structures with minimum simulation costs. **Jeoung-Hee et al. [6]** examined the response of a composite laminate to high-velocity impact by employing LS-DYNA software. The study utilized a surface-to-surface eroding contact algorithm to investigate and simulate the interaction dynamics between the impactor and the laminate. It is observed from the results that the layers in the element are eroded when the stress level reaches the stated failure condition. **Fatih Dogan et al. [7]** conducted an analysis of the low-velocity impact response of Fiber-Reinforced Polymer (FRP) laminated composite structures. Recognizing the significance of predicting and preventing the adverse effects of impacts on

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ground and space vehicles. The numerical results were validated against experimental outcomes, specifically focusing on energy and force parameters. These validated numerical results have played a crucial role in establishing modeling and impact simulation guidelines for FRP laminate composites. **Muhammad Ilyas et al. [8]** investigated a method for correlating critical energy release rates, employing a combination of numerical simulation and experimental data. Quasi-static and pseudo-dynamic loading rates were applied in the experimental phase to observe the mode I critical energy release rate. The study utilized cohesive modeling techniques to predict the progression of delamination in a composite laminate consisting of carbon fiber and epoxy resin. **Sanan et al. [9]** investigated the impact of metal layer distribution in glass fiber reinforced aluminum laminates subjected to low-velocity impact. The study involved both experimental testing and finite element analysis to comprehend the material behavior. The findings revealed that placing a thinner metal layer on top of the laminate and distributing it throughout the layup had the effect of reducing the impact resistance of GLARE (Glass Laminate Aluminum Reinforced Epoxy). **Mark K. Hazzard et al. [10]** employed finite element analysis (FEM) to simulate the behavior of Dyneema-HB26 fiber composite materials under various conditions, including quasi-static rates of deformation, low-velocity drop weight impact, and high-velocity ballistic impact. The analysis revealed that within the impact zone, the failure processes mirrored those observed in ballistic impact, encompassing large-scale delamination, fiber failure, and shear pull-in. Additionally, a mode switch between local progressive failure and bulge deformation was observed, triggered by the projectile and the laminate reaching a critical contact force. **Sebastian et al. [11]** conducted both experimental and numerical analyses, focusing on the impactor's geometry. The numerical results were used to analyze the energy absorption of the composite during impact, with a particular focus on the impactor's geometry. The findings indicated that the size of the delaminating area was entirely contingent on the impactor's geometry. Furthermore, it was observed that the diameter of the delaminating area exhibited correlation with the extent of damage in the reinforcing layers. **Wang et al. [12]** conducted numerical and experimental investigations to verify the impact response of laminated aluminum composite structures. It is evident from the three-point bending tests that failure modes are characterized by significant plastic deformation, delamination, and local buckling on the top aluminum layers. The local buckling was attributed to compressive stress from bending moments, and the maximum plastic strain was observed on the top and bottom aluminum layers. Notably, in transverse three-point bending, unlike normal three-point bending, the maximum plastic strain in the adhesive occurred in the top region. **Ali Rabiee et al. [13]** investigated various parameters within FEA techniques to simulate the impact behavior of epoxy/glass tubes with dissimilar material models. The study revealed that finite element analysis predicted a commendable energy absorption capability, demonstrating a high level of accuracy when compared with experimental results. It is evident that conducting the experiments to evaluate the impact damage of composite structures is tedious and cumbersome and quite expensive. Therefore, in this research work attempts are made to use computational methods capable of accurately predicting the impact response of composite structures. However, it is crucial to emphasize that the analysis and numerical methodologies employed must undergo validation through comparison with previous results. This validation process ensures the reliability and accuracy of the computational methods in predicting the impact response of composite structures. Hence, in this research, LS-DYNA **[14]**, a simulation software, is employed to investigate the effects of ply delamination in Dyneema composite models. The study utilizes *MAT-59 and *PART_COMPOSITE, incorporating 3-D elements for a comprehensive non-linear ballistic impact dynamic analysis.

2. NUMERICAL SIMULATION USING LS-DYNA

Setting up procedures for numerical simulations, several assumptions and considerations are need to be taken into account to ensure the accuracy and reliability of the results. To estimate and model delamination damage mechanisms in composite materials the following factors are considered to accurately capture the behavior and progression of delamination.

- Damaged part strength with residual stiffness
- Mitigation of load in the impact zone
- Characteristics of the damaged component's capacity to be re-used

These considerations enable engineers to predict and design the structural integrity of vital structures that frequently experience impacts. Moreover, projectiles with higher impact velocities can cause significant harm and, in specific instances, result in catastrophic failure. With the advancement of FEA, tools like LS-DYNA and other FEA software can be used to my engineering problems. In this research, the LS-DYNA simulation software is employed to examine the delamination behavior of Dyneema composites.

2.1 Dyneema Composite Damage Modeling

The LS-DYNA material model MAT-162 has been specifically crafted for the analysis of damage and delamination in composites. It necessitates a distinct license and is not accessible through commercial channels. To address this challenge, an alternative modeling approach using *MAT-59 was implemented to simulate failure criteria for both fiber and matrix **[6, 7]**. This approach involved the integration of elastic-plastic material zones and the establishment of corresponding failure criteria, as outlined by equations 1-4.

Tensile fiber failure mode:

$\sigma_{aa} > 0, then$

$$\sigma_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0\ failed \\ < 0\ elastic \end{cases} \qquad (1)$$

After failure, $E_a = E_b = G_{ba} = \vartheta_{ab} = \vartheta_{ba} = 0;$

Compressive fiber failure mode:

$\sigma_{aa} < 0, then$

$$\sigma_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \begin{cases} \geq 0\ failed \\ < 0\ elastic \end{cases} \qquad (2)$$

After failure, $E_a = \vartheta_{ab} = \vartheta_{ba} = 0;$

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Tensile matrix failure mode:

$\sigma_{bb} > 0, then$

$$\sigma_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0\ failed \\ < 0\ elastic \end{cases} \quad (3)$$

After failure, $E_b = \vartheta_{ba} = 0 \rightarrow G_{ab} = 0;$

Compressive matrix failure mode:

$\sigma_{bb} < 0, then$

$$\sigma_m^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right] \frac{\sigma_{bb}}{Y_c} + + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0\ failed \\ < 0\ elastic \end{cases} \quad (4)$$

After failure, $E_b = \vartheta_{ba} = \vartheta_{ab} = 0 \rightarrow G_{ab} = 0;$

In this context, the failure mechanism operates by considering the progressive combinations of these criteria, encompassing tension and compression in the longitudinal and transverse directions. Additionally, it accounts for the through-thickness direction involving compression and shear stresses.

2.2 Ply Delamination Modeling

Several options are available for modeling delamination in LS-DYNA, such as Cohesive modeling and the Tie-Break model. Tie-Break contact algorithms is extensively used due to its robustness in predicting composite delamination. Consequently, Tie-Break model is adopted in this research work. As the name indicates that an algorithm initiates the tying of nodes that are initially in contact by creating a linear spring, as illustrated in **Figure 2**. When the maximum stress threshold is reached, surface debonding initiates, resulting in a linear damage curve that scales down the stress until the critical separation is achieved. Subsequently, the spring is eliminated and verification is conducted at each segment to identify instances of delamination between the elements in the upper and lower sub-laminates. In the tiebreak failure process, Mode-I fracture is observed as a predominant mode of failure. The energy release rate in Mode-I (G_{IC}) is utilized to ascertain the critical normal separation of the surface, while the critical shear stress (Mode-II) is dependent on the inter-laminar damage. Further, better results can be achieved by incorporating the Coulomb friction during the transitional phase from static to dynamic friction.

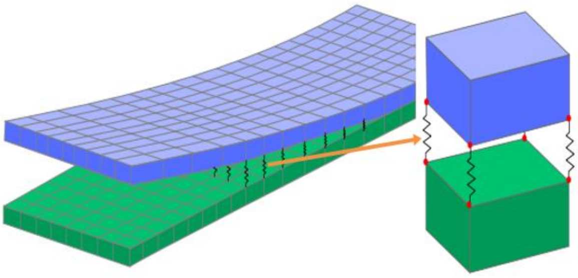

Figure 2: Nodes Tied by Linear Spring

2.3 Tie-Break Failure Criteria

The Tie-Break failure criteria is employed to predict the delamination between elements in FEA. In this context, σ_n and σ_s represents normal and shear stress acting at the interface, while NFLS and SFLS denotes maximum normal and shear stress at the tie contact points. Tie break contacts, designed to transmit both compressive and tensile stresses with variable failure criteria, serve as a tool to simulate interlaminar debonding. By establishing springs between two surfaces, the tiebreak function enables the contact surfaces to break after attaining the maximum normal stress (NFLS) or shear stress (SFLS) with the initiation of damage. Subsequently, the two surfaces begin to separate, and other parameters related to tiebreak interface failures, energy release rate, and delamination propagation at the ply interfaces are observed and Equation-5 represents the condition for the tie-break criteria.

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_{ns}|}{SFLS}\right)^2 \geq 1 \qquad (5)$$

2.4 Boundary conditions for Impact Simulation

The LS-DYNA explicit solver, along with its standard cards including *Boundary, *Initial, and *Contact (penalty contact algorithm), was employed. Additionally, *Control cards were implemented to mitigate numerical errors.

2.5 Validation of Numerical Simulation Results

To examine and validate the current methodology for effective delamination and load-deflection output, a cantilever beam having cross section of (20 x 6) mm with 24 layers was created and a loading cylinder of diameter 6.4 mm is positioned at a distance of 10 mm from the free end of a cantilever beam as illustrated in **Figure 3**.

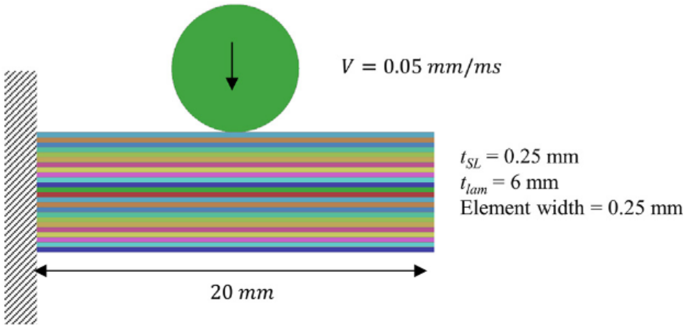

Figure 3: Short beam shear model for Validation [10]

3. MODELLING FOR BALLISTIC IMPACT

In the current research, a rectangular plate measuring (300x300x1.25) mm was used, consisting of 16 layers with an alternating stacking orientation of 0°/90°/0°/90° for the 16 plies. A projectile with a diameter of 20 mm was utilized as the impactor, as depicted in **Figure 4.** The impactor is made of Ti-6Al-4V alloy, a material commonly utilized in various industries. The initial velocity of the impactor is assigned to the part using the *INITIAL card in LS-DYNA.

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To ensure a better correlation with the MAT-162 model **[10]**, the laminate was secured by clamping it on all edges, and a symmetric boundary condition was applied along the middle axis of the entire model.

The stress wave propagation, coupled with the impact force on a target structure, exhibits highly non-linear behavior. In LS-DYNA explicit analysis, the time-dependent phenomenon is effectively managed by incorporating the ERODING-NODE-TO-SURFACE contact option between the impactor and the composite target **[14]**. The penalty approach employed in the analysis accommodates variations in the mechanical characteristics of the contacting bodies and addresses other non-linearity.

The geometry was discretized using eight-noded hexahedral elements. To address hourglass issues, a modeling approach with fully integrated elements was incorporated. Standard control cards, including Energy control and contact stability, were employed to eliminate numerical instability in the model **[14]**. Further, the effects of several numerical factors such as damping, analysis, and other control values have been examined in order to suppress non-convergence effects, special attention was given to hourglass control to prevent any negative impact on the model.

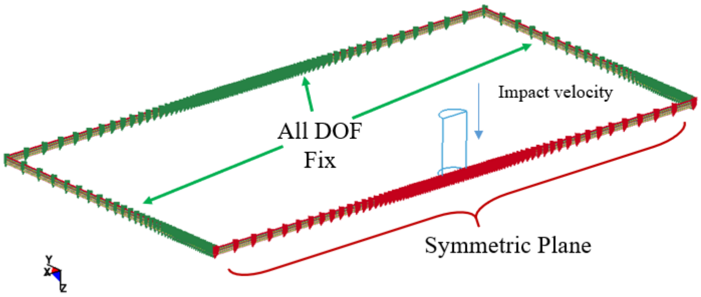

Figure 4: Boundary condition for Ballistic impact

4. RESULT AND DISCUSSIONS

In LS-DYNA, the tiebreak delamination contact feature is employed to simulate the debonding of laminated composite plates between sub-laminates. Tiebreak contacts serve as adhesives, connecting the sub-laminates in LS-DYNA models. The material damage during loading is directly proportional to the distance between the initially contacting parts. Upon reaching the critical opening, the contact between the sub-laminates is severed, leading to the separation of the sub-laminates into two independent surfaces. Normal surface-to-surface contact is subsequently established to prevent penetration.

4.1 Load Deflection and Stress Analysis Short Beam Shear Model

Figure 5 illustrates the load-deflection characteristics of composites subjected to ballistic impact, obtained from LS-DYNA simulation software. The results are compared with experimental data and LS-DYNA simulations utilizing MAT-162. The initiation of reduced load-carrying capacity in short beam shear is analyzed through the propagation of Mode II

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cohesive interface strength. It is noted that inter-laminar damage in the laminates is not observed as the Mode II shear strength increases, leading to an improvement in the load-carrying capacity of the beam. This phenomenon is clearly depicted in the load-deflection curves. Further, it is noted that the experimental and simulation results align well with the developed model initially, but deviate as the deflection increases. This deviation can be attributed to the propagation of delamination and the subsequent breakage of tiebreak contacts with less load after the initiation of delamination.

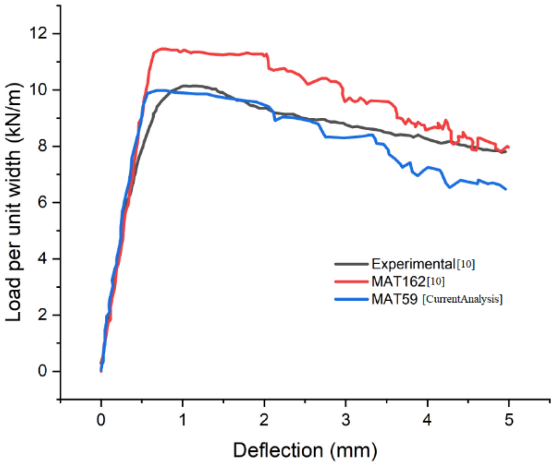
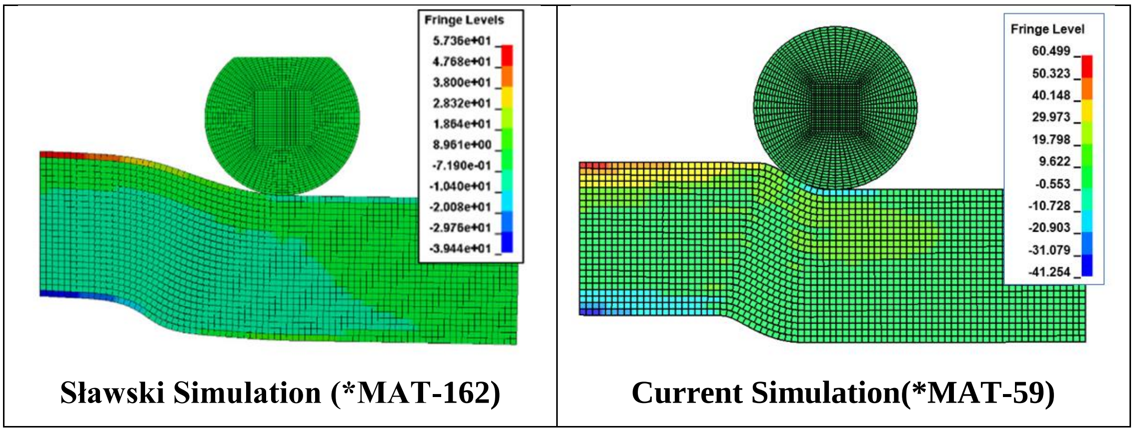


Figure 5: Load deflection curve for short beam shear model

Figure 6 displays the fringe levels obtained from the analysis of a short beam shear model using LS-DYNA. The study involved the application of two material models: *MAT-59 and the MAT-162 reference model proposed by **Sławski [10]**. The findings indicate that the proposed model employing *MAT-59 aligns well with previously published results. Additionally, it is clear that delamination is predominantly observed in the region where the cylinder and laminate come into contact. Hence, the proposed model is utilized to conduct ballistic impact by varying the impact velocity.



Sławski Simulation (*MAT-162) **Current Simulation(*MAT-59)**

Figure 6: Axial stress of Short Beam Shear model

4.2 Ballistic Impact

A composite plate measuring 300x300x1.25 mm, consisting of 16 layers arranged in an alternating stacking sequence of 0°/90°/0°/90°, was used to conduct an LS-DYNA simulation. The study aimed to analyze the impact load while varying the impact velocity, utilizing a 20 mm diameter impactor. It is noticed a progressive local failure on the front face of the impact zone has been observed, leading to bulging membrane action and significant delamination. Additionally, in the impact zone, the laminates region away from the contact zone exhibits negligible deformation. However, the laminates section at the impact zone tends to delaminate, initiating from the top surface and propagating towards the bottom surface due to the direction of the fibers being in contact with the projectile.

Figure 7 emphasizes the delamination of the plies at a velocity of 300 m/s. The initiation of delamination begins at the center and extends outward from the impact zone. Furthermore, it is noted that for velocities below 250 m/s, the delamination area was comparatively smaller. Delamination accompanied by perforation was observed for impact velocities exceeding 500 m/s, as illustrated in **Figure 8**. In this scenario, perforation predominates over delamination, primarily due to the projectile carrying substantial kinetic energy concentrated on a smaller area.

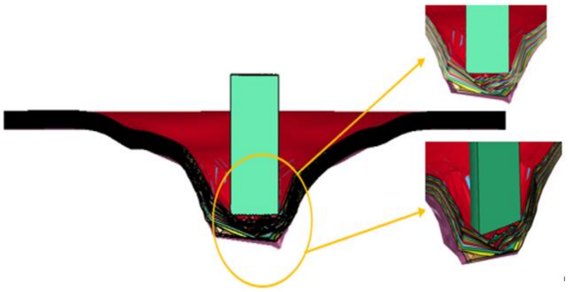


Figure 7: Delamination of plies with impact velocity of 300 m/s

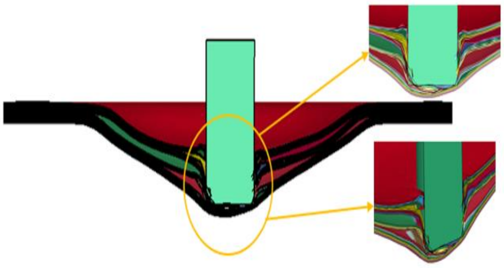


Figure 8: Delamination with perforation with impact velocity above 500m/s

Figure 9 presents the time-domain contact force dynamic response for an impact speed of 365 m/s. It is observed that the contact forces developed during the impact, as simulated by LS-DYNA and the methodology outlined in the publication using MAT-162 and MAT-59, are in good agreement.

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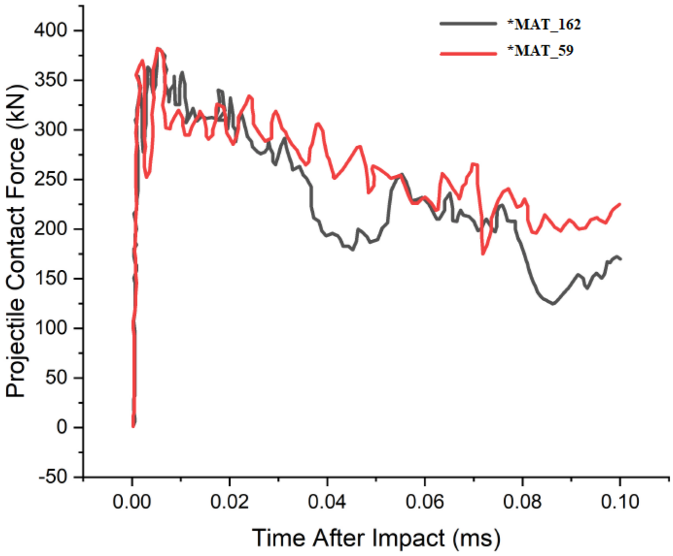

Figure 9: Contact forces at the impact zone with an impact velocity of 365 m/s [10]

Figure 10 highlights the internal energy observed by the Dyneema composite. It is clear that at impact speeds of 100 m/s and 200 m/s, the composite material successfully stops the projectile without any significant damage or perforation to the composite structure. However, at 300 m/s, notable damage with perforation is observed in certain layers, and the material is incapable of withstanding the impact force, resulting in progressive failure. Additionally, it is noted that the material experiences escalated delamination and penetration beyond 250 m/s. Therefore, the utilization of Dyneema composites within the impact velocity range of 100 m/s to 200 m/s proves effective in withstanding damage and deformations, rendering it well-suited for various applications.

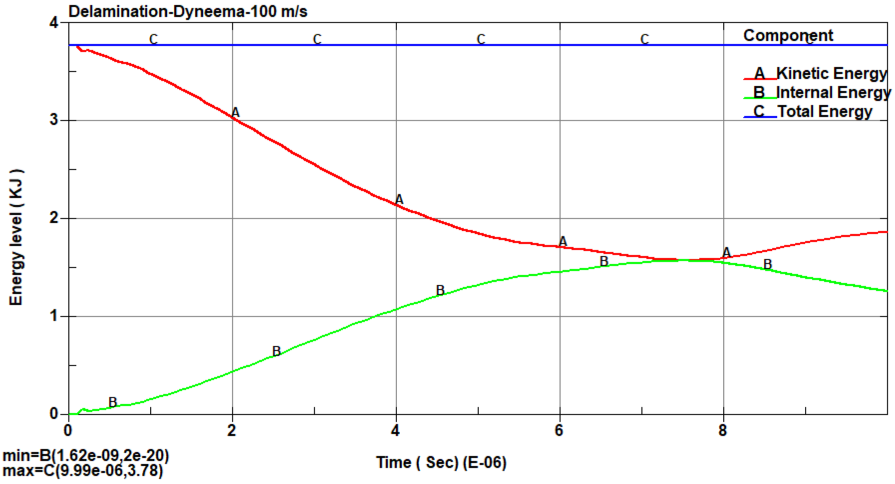

Figure 10 (a): Impact velocity of 100 m/s

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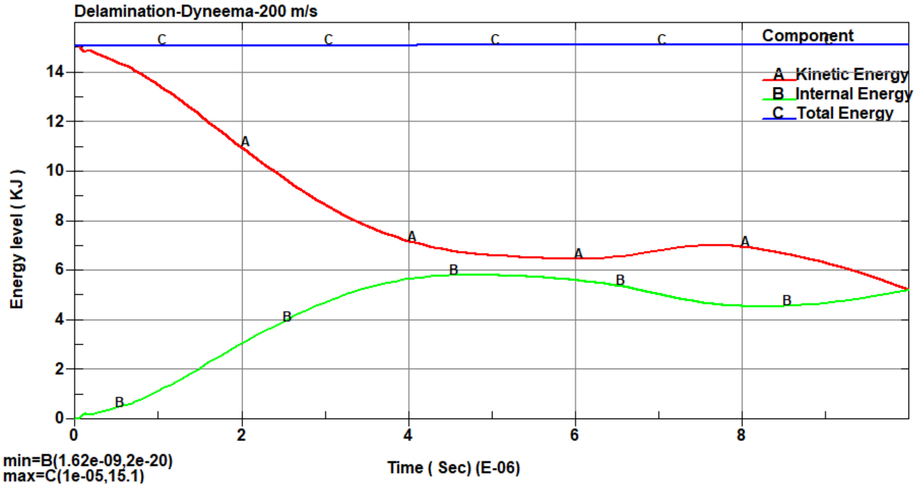

Figure 10 (b): Impact velocity of 200 m/s

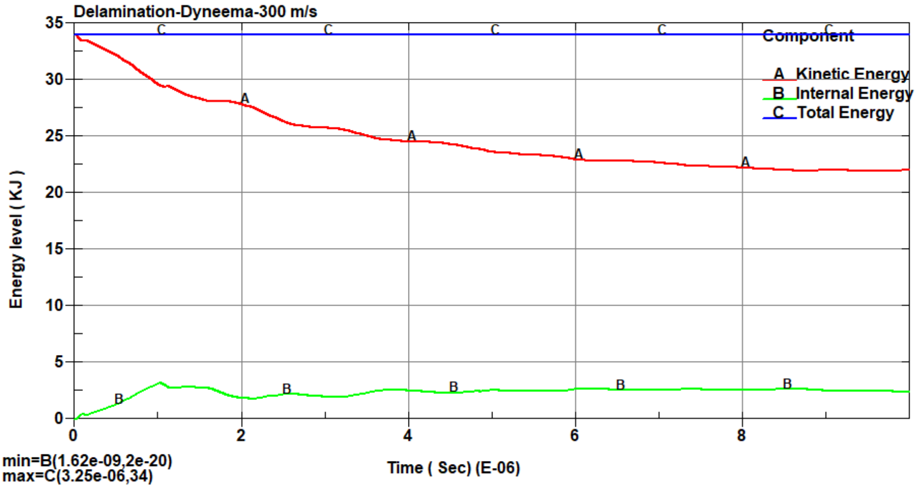

Figure 10 (c): Impact velocity of 300 m/s

Figure 10: Energy observed by Dyneema composite for different Impact velocities

5. CONCLUSION

The delamination behavior of a DYNEEMA composite laminate is investigated using the LS-DYNA finite element software. The analysis employs *MAT-162 and *MAT-59 material models by varying impact velocity. It is evident that the results obtained using MAT-59 material model are in good agreement with the published results. Further, delamination and contact force at the impact region were observed by varying the impact velocity, specifically at 100 m/s, 200 m/s, and 300 m/s. At impact speeds of 100 m/s and 200 m/s, the Dyneema composite material successfully stops the projectile without any significant damage or perforation to the composite structure. However, at 300 m/s, notable damage with perforations are observed in certain layers, and the material is incapable of withstanding the impact force, resulting in

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progressive failure. Conducting damage analysis for composite structures necessitates essential components such as Mode-I crack simulations, convergence of FEA solutions, and the implementation of contact tiebreak definition.

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