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Delamination Behavior of Dyneema Composite Laminate due to High Velocity Impact using LSDYNA

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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 LSDYNA. 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*

1.0 Introduction

Due to their high stiffness and strength-to-weight ratios, composite materials, especially laminated fabrication, are becoming more popular for aircraft structures. Also, another important application of composite is to be the primary member of Energy Absorbers. Wherever there is a risk of damage to critical machine components, potential health, or safety, energy-absorbing systems are installed. Energy-absorbing shields are already employed in a variety of industries, including energy, automobile, rail, aviation, mining, and maritime transportation. Whenever it concerns to energy-absorbing shields, the aviation and military industries have the highest demands. Depending on the use, composite shields may be subjected to a variety of situations such as small stones/pebbles, hail stones, birds, gunfire, or explosive debris, which can cause significant damage, which in turn helps to reduce the damage to other load bearing members.

Of such, the current work focuses on a new material called Dyneema®. It is a fiber composite made of Ultra-High Molecular Weight Polyethylene (UHMWPE) that is currently used in a wide range of industrial application[1]. The light weight and superior strength of this material distinguish it from other composite materials. When comparing weight to strength, Dyneema is up to 15 times stronger than steel and 40% stronger than aramid fibers. This Polyethylene fiber also has a high modulus, which means it can offer maximum strength while being lightweight. Dyneema fiber is made using a proprietary gel spinning process that 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 contains exceptionally long molecular chains that effectively transfer load to the polymer backbone. As a result, it is stronger at the same weight or lighter at the same strength than any other alternative. Due to these

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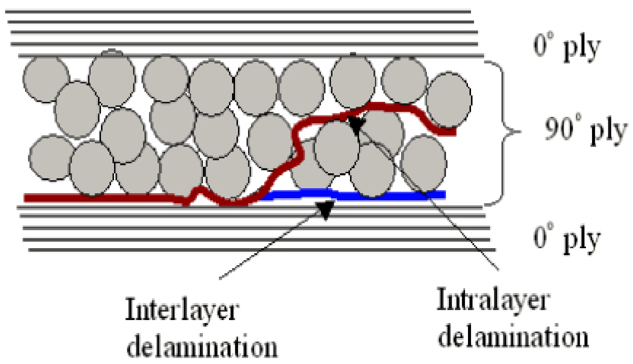


Figure 1. Damage caused due to Delamination in composite material[6].

superior qualities, this material makes an ideal choice for Aerospace and Military applications.

There are many modes of failure observed in composite material and delamination is the commonly observed mode as shown in Figure 1. Ply delamination can decrease a structure's strength, stiffness, and resistance to buckling. A separation failure between two adjacent plies characterizes an interlaminar delamination. When failure occurs within a ply, a second delamination failure mode known as intralaminar delamination may occur. In most scenarios, "delamination" refers to interlaminar failure, whereas "matrix cracking" refers to intralaminar crack propagation. Both failure modes are due to the defects in the bond which is present in between the lamina/laminate (or constituents in the composite itself) and ultimately leads to a complete structural failure.

Many researchers have worked analyzing the delamination and damage behavior of the plies. An effort has been made to understand the previous methodology used and are discussed below.

Rajbhandari *et al.*,[2] utilized experimental results to predict delamination and in-plane damage to correlate the effectiveness of the modelling technique using various analyses and modelling software like FE code, LS-DYNA. The stacked shell element approach is best applied when a potential delamination interface can be predicted. The predicted force-time result was within that of experimental results. The predicted damage area was within 20% of the experimental results. Bazle A. Gama *et al.*,[3] studied the damage characterization on plain weave S-2 Glass and SC15 epoxy composite thick-section laminate simulations using Experimental tests under quasi-static punch shear loading LS-DYNA. The TIE-BREAK boundary option method for modeling and delaminating was also analyzed. Reasonable agreement between experimental and simulated results was obtained. Robin Olsson *et al.*,[4] studied a criterion which is expressed for delaminating onset in transversely isotropic laminated plates having small mass and high velocity impact. The estimated delaminating threshold loads and velocities correlate well with the FEA models, with fairly good agreement for the plate thicknesses studied, which range from 2 to 6 mm. Fleming *et al.*,[5] studied the application of LS-DYNA to specific modelling procedures of graphite/epoxy composite materials to study inter laminar and delamination failure using different approaches. Results of this study showed that achieved efficiency with the presented model is a part of the effort of improving realistic simulation of the mesoscale model of composites structure with acceptable simulation costs. Ahn J. H. *et al.*,[6] using LS-DYNA software investigated the high-velocity impact response of a composite laminate. A surface-to-surface eroding contact algorithm was used to study and simulate the interaction between the impactor and the laminate. The layer in the element is eroded when the stress level reaches the stated failure condition. Fatih Dogan *et al.*,[7] analysed the low velocity impact response of Fibre Reinforced Plastic (FRP) laminated composite structures and predicting and preventing the negative effects of impact on these structures are paramount design criteria for ground and space vehicles. The Numerical results were validated with experimental results in terms of energy and force. The numerical results have been used to develop modelling and impact simulation guidelines for Fiber Reinforced Polymer Laminate Composites, offering recommendations on modelling and simulation aspects such as the number of shell sub-laminates, element size, and contact stiffness scale factors. Muhammad Ilyas *et al.*,[8] studied the method for critical energy release rate correlation utilising both numerical simulation and experimental results. For the experimental results, quasi static and pseudo dynamic loading rates were utilised to observe mode I critical energy release rate. The progression of delaminating in a carbon fibre and epoxy resin composite material was predicted using cohesive modelling technique.

Khan Sanan *et al.*,[9] considered the effect of metal layer distribution in glass fibre reinforced with aluminium laminates which were subjected to low velocity impact.

Both Experimental and Finite element analysis were carried out to understand the behaviour. It was noticed that placing a thinner metal layer on top of the laminate and distributing it throughout the layup reduces GLARE's impact resistance.

FEM analysis was utilised by Mark K. Hazzard *et al*.,[10] to simulate the behaviour of Dyneema-HB26 fibre composite materials under quasi-static rates of deformation, low velocity drops weight impact, and high velocity ballistic impact. Within the impact zone, the failure processes were identical to those seen in ballistic impact, with large scale delamination, fibre failure, and shear pull-in. A mode switch between local progressive failure and bulge deformation was also observed, which was induced by the projectile and the laminate reaching a critical contact force. Sebastian Sławski *et al*.,[11] conducted experimental and numerical analysis which focused on the influence of the impactor's geometry. Based on the results from numerical research, energy absorption of the composite during impact depending on the impactor geometry was analysed. It was found that the size of the delaminating area completely depends on the impactor geometry. Also, it was also noted that diameter of the delaminating area is correlated to the amount of damage in the reinforcing layers. J Wang *et al*.,[12] performed Numerical and experimental verification of impact response of laminated aluminium composite structure. It was found that for the transverse three-point bending tests, the failure modes of large plastic deformation, delamination, and local buckling on the top aluminium layers were observed. The local buckling was induced by the compressive stress from the bending moments, and the maximum plastic strain occurred on the top and bottom aluminium layers. However, unlike the normal three-point Bending, the maximum plastic strain in the adhesive for transverse three-point bending occurred in the top region. Ali Rabiee *et al*.,[13] studied different parameters in FEA techniques to simulate the impact behaviour of epoxy/glass tubes with dissimilar material models. Finite element analysis predicted good energy absorption capability with a good level of accuracy when compared with Experimental results.

One of the most significant disadvantages of utilizing composite structures is their vulnerability to impact damage. Understanding their behavior, particularly failure mechanisms subjected to impact loading, is therefore crucial if the entire benefit of employing composites is to be achieved. Because experimental research is quite expensive, there is a need for reliable computational methods that can predict the impact response of composite structures. The following factors should be considered when estimating the damage limit's potential tolerance:

- 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 procedures ensure that engineers can appropriately anticipate and design the structural integrity of critical structures that are frequently subjected to impacts. Furthermore, any projectile with a higher impact velocity can inflict substantial damage and, in certain

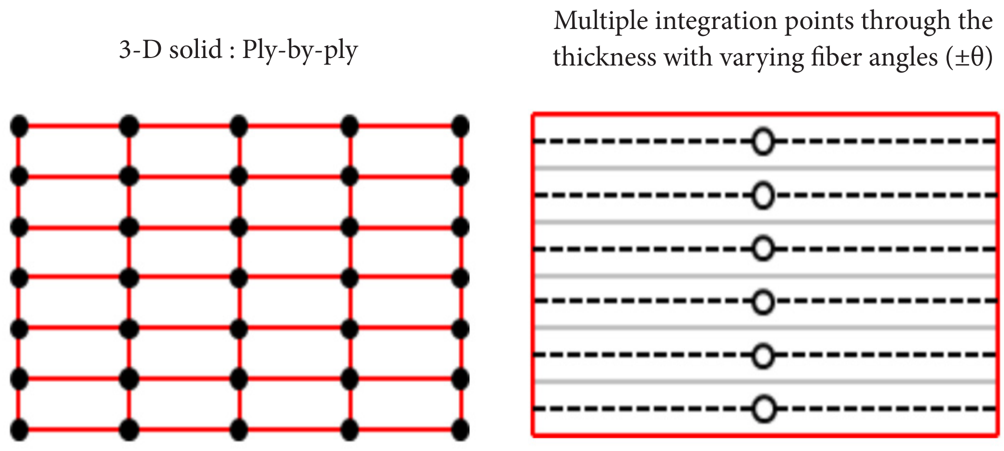


Figure 2. Delamination approach by solid modelling of composite layers[14].

cases, can lead to catastrophic failure. This illustrates how crucial this topic is, and how predicting impact force and stresses will assist us in engineering damage-resistant structures. With the advancement of finite element software tools and hardware computing capacity, it is now more feasible to leverage such tools to construct finite element algorithms for predicting these behaviors. However, it is critical to note that the analysis/numerical methodologies must be validated by comparing them to previous results. Advanced computational methodologies are vital for any defense sector to reduce the time required for suppliers to accomplish typical military certification and the related expenses.

The aim of this current work is to develop a methodology for 3D-FE Dyneema composite model using *MAT_59 and to perform non-linear Ballistic impact dynamic analysis to study the effect of ply delamination as highlighted in Figure 2.

2.0 Numerical Simulation using LS-DYNA

The high-fidelity explicit simulation platform LS-DYNA is used in this study to evaluate the proposed for delamination effects observed in the composite material. *PART_COMPOSITE with 3-D elements was consider and other details are briefly addressed in the following sections.

2.1 Composite Damage Modeling

A newly implemented Material model: MAT_162, has been developed for analyzing damage and delamination of composites. But this requires a special license and is not commercially available. In order to mitigate this issue and come up with alternate modeling, the current work utilizes *MAT_59 which is a composite failure material model. This model is based on the enhanced version of MAT_22 and also includes the elastic-plastic material zones and the failure criteria are explained in Figure 3. Damage to composite structures is very complex scenarios that occur as a consequence of failure mechanisms such as fiber breaking, fiber buckling, matrix cracking, fiber-matrix debonding, and delamination.

Here the failure works based on the progressive material failure combinations of these criterions and are typically inclusive of tension and compression in longitudinal and transverse directions, respectively. An also through-thickness direction in compression and shear stresses.

2.2 Ply Delamination Modeling

There are multiple options to model delamination in LS-DYNA like Cohesive modeling, Tie-Break model etc. Based on the literature survey, it was observed that Tiebreak contact algorithms are relatively robust and help in predicting the delamination of the composite and was

- tensile fibre failure mode:

$\sigma_{aa} > 0$ then

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

after failure $E_a = E_b = G_{ba} = v_{ab} = v_{ba} = 0$;

- compressive fibre failure mode:

$\sigma_{aa} < 0$ then

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

after failure $E_a = v_{ba} = v_{ab} = 0$;

- tensile matrix failure mode:

$\sigma_{bb} > 0$ then

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

after failure $E_b = v_{ba} = 0 \rightarrow G_{ab} = 0$;

- compressive matrix mode:

$\sigma_{bb} < 0$ then

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

after failure $E_b = v_{ba} = v_{ab} = 0 \rightarrow G_{ab} = 0$;

Figure 3. *MAT 59 Failure Criteria for both Fiber and Matrix[6,7].

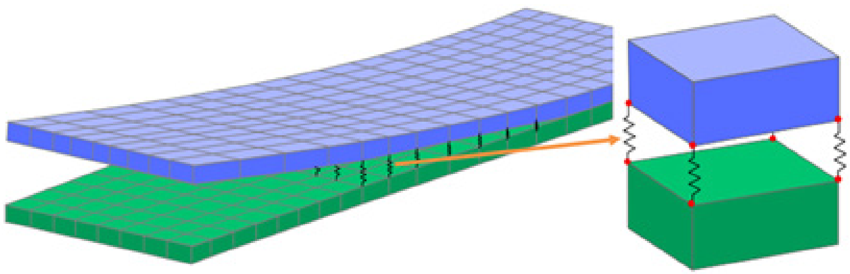


Figure 4. Nodes Tied by Linear Spring.

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geq 1$$

Figure 5. Tie-Break failure criteria.

utilized in the present study. Here, the algorithm initially ties nodes that are originally in contact by generating a linear spring as Highlighted in Figure 4, and when the maximum stress threshold is met, the debonding of the surface begins, that leads to a linear damage curve scaling down of stress until the critical separation is established and thus the spring becomes eliminated[14]. Verification is performed between each segment as the finite element numerical solution evolves in time to detect whether delamination has occurred between the elements in the upper and lower sub laminates. During the tiebreak failure process, Mode-I fracture is also observed as a dominating mode of failure. The energy release rate in Mode-I (GIC) is used to determine the critical normal separation of the surface and the critical shear stress (Mode-II) that is dependent on the inter-laminar damage. Better results can be obtained if Coulomb friction formulation is utilized while the transition phase of static to dynamic friction occurs.

Here, σ_n and σ_s are the normal stress and shear stress acting at interface, while are the normal and shear strength of the tie contact and the critical distance of the bond respectively. Tiebreak contacts, which transmit both compressive and tensile stresses with variable failure criteria, can be used to simulate interlaminar de-bonding. 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). Following this, the two surfaces begin to separate once the damage is initiated, while the other parameters based on the tiebreak interface failures with energy released rate represents the propagation of the delamination failure in the ply interface.

3.0 Boundary Conditions for Impact Simulation

Utilizing the LS-DYNA explicit solver and its available standard cards such as, *Boundary, *Initial *Contact (penalty contact algorithm) were utilized. Also, *Control cards were implemented to avoid numerical errors.

3.1 Short Cantilever Beam Condition for Validation

To study and validate the current methodology of the effective delamination and load-deflection output, 24

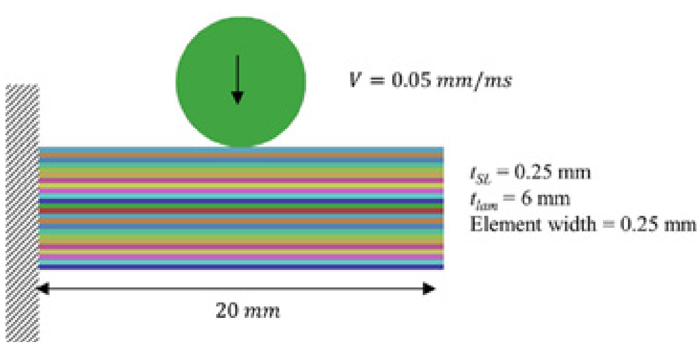


Figure 6. Representative short beam shear model for Validation[10].

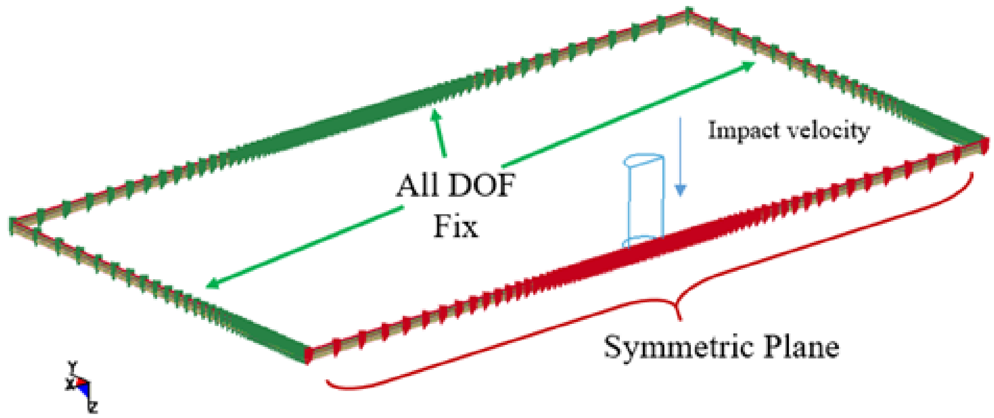


Figure 7. Boundary condition for Ballistic impact.

layers cantilever loaded beam were modelled. The beam was 20 mm wide, with a 6.4 mm loading cylinder diameter 'd' at a distance 's' of 10 mm from the free end and a total laminate height 'h' of 6 mm as highlighted in the Figure 6.

3.2 Modelling for Ballistic Impact

A dimension of 300x300 mm is utilized with 16 layers, where the total thickness was around 1.25mm. The stacking orientation implemented is 0°/90°/0°/90° alternatively for 16 plies. Also, a 20mm projectile diameter was considered for the impactor which is as shown in Figure 7. The Impactor material considered is Ti-6Al-4V alloy because the properties lies in between that of Aluminium and steel and also another common material used in the industries. Velocity was given directly to the part using *INTIAL card. In order to reduce the time taken for the explicit impact analysis, Half-Symmetry model approach was utilized. In Order to have a good correlation with the obtained reference results of Ls-Dyna Mat 162 model literature[10], the laminate was clamped on all the edges and symmetric boundary was evoked on the middle axis of the entire model.

The stress wave propagation paired with impact force on a target structure is highly non-linear in nature. This time-dependent behaviour can be handled with LS-DYNA Explicit general contact feature, which seamlessly incorporates the ERODING-NODE-TO-SURFACE contact option between the impactor and the composite target[14]. The penalty technique utilised in this algorithm allows for differences in the mechanical characteristics of the contacting bodies as well as other non-linearity's. Eight noded hexahedral solid elements were used to mesh the parts. To avoid any hourglass issues, the modelling approach utilizes fully integrated elements. To eliminate numerical instability in the model, standard control cards such as Energy control and contact stability were incorporated[14].

The effects of several numerical factors such as damping, analysis, and other control values have been examined in order to suppress any numerical non-convergence effects, particularly hourglass control, which would have a negative impact on the model.

4.0 Result and Discussion Numerical Simulation using LS-DYNA

In the LS-DYNA tool, tiebreak delamination contact between sub laminates may be used to simulate the debonding of laminated composite plates. Tiebreak contacts are used as an adhesive to connect the sub laminates in the LS-DYNA models. The material's damage during loading is proportional to the distance between the two parts that were initially in contact. When the critical opening is achieved, the contact between both the sub laminates will be disconnected, and the sub laminates will be separated into two independent surfaces with normal surface to surface contact to prevent penetration.

4.1 Validation of the Current Methodology

The initialization of reduced load carrying ability in short beam shear is examined by propagation of Mode

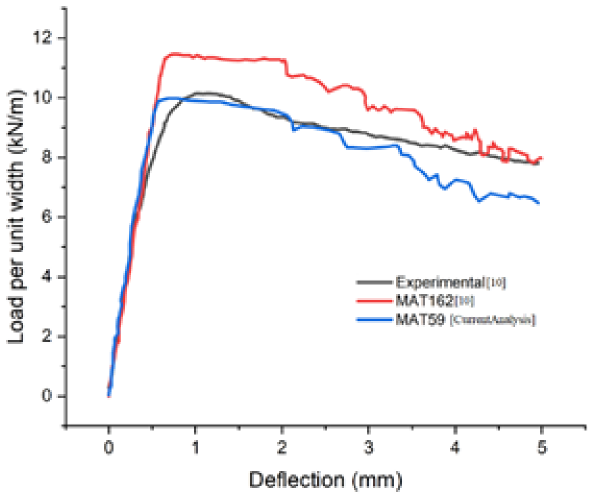


Figure 8. Load deflection for short Beam Loading.

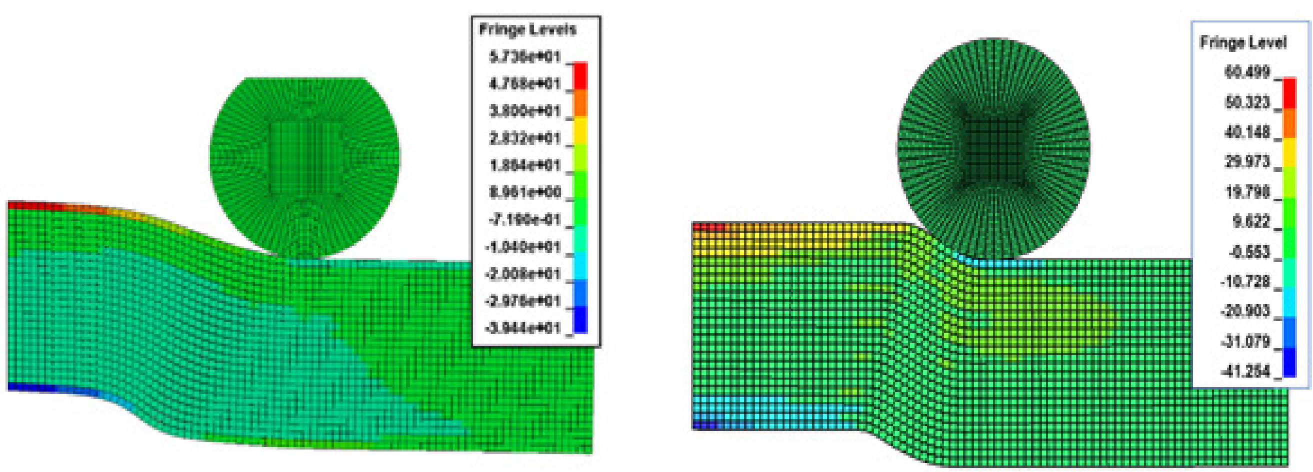
II cohesive interface strength. Inter-laminar damage was deferred as Mode II shear strength increased, and the load required to delaminate the beam improved, which can observe in the load deflection curves shown in Figure 8. The Current methodology matches initially well with the Experimental result but deviates as the deflection increases. This can be attributed to propagation of delamination and breaking of the tiebreak contact with less load after the onset of delamination.

The comparison of axial stress for the short beam loading is as shown in Figure 9. It can be seen that the current approach and the reference results are in good agreement[10]. Localized delamination is observed and is only pre-dominant at the region of contact.

4.2 Ballistic Impact

There is a progressive local failure on the front face of the impact zone, resulting in bulging membrane action and considerable amounts of delamination. In the impact zone, laminates region away from the contact zone show negligible deformation, whereas laminates section at the impact zone tend to delaminate starting from the top surface and propagate to the bottom surface because the direction of the fibres is in contact with the projectile. Figure 10 highlights the delamination of the plies at 300 m/s. the onset of the delamination starts from the center and moves away from the impact zone. It's also observed that for velocities less than 250m/s, delamination area was less. Delamination with Perforation was observed for impact velocities more than 500 m/s as shown in Figure 11. Here predominately Perforation was more rather than Delamination since projectile has enormous kinetic energy, which will be acting on small area.

Impact energy (i.e. kinetic energy) is transformed to strain energy (internal energy) due to plastic deformation and also released as elastic vibrations at the supports. It is observed that localized membrane at the impact zone will undergo bending and shear local plastic deformation, which finally leads to delamination. These forces are highly non-linear in behaviour, which makes solving by analytical methods very difficult. In Figure 12, the time-



Reference Simulation: *MAT_162 [10]

Current Simulation: *MAT_59

Figure 9. Comparison of X-stress of Short Beam.

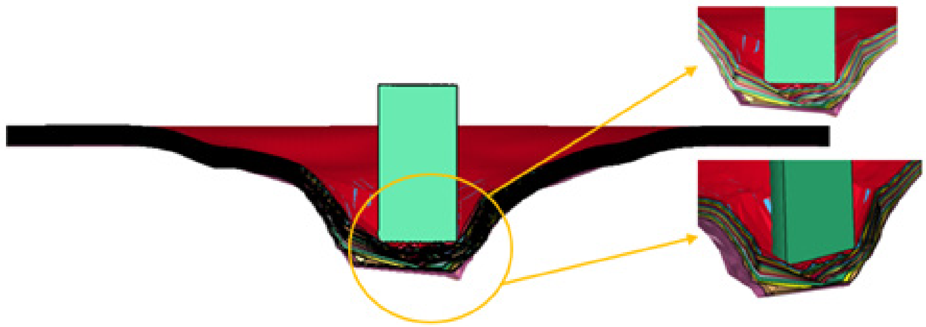


Figure 10. Delamination of plies at 300 m/s.

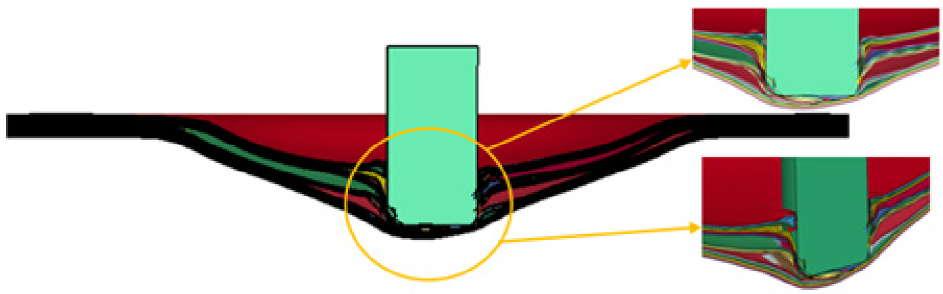


Figure 11. Delamination with perforation at high velocity (above 500m/s).

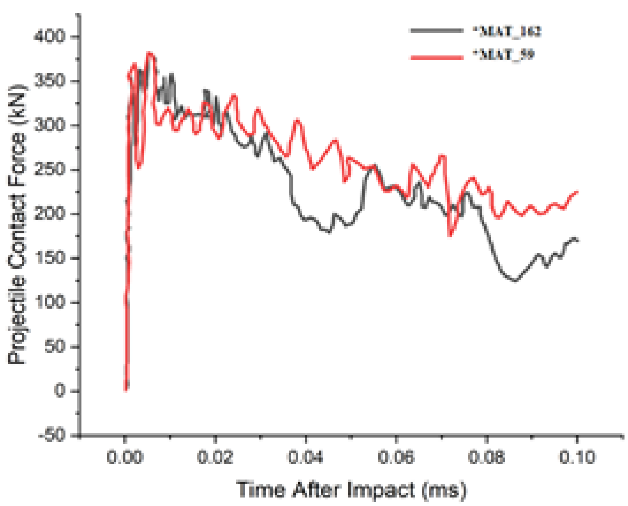


Figure 12. Comparison of contact forces for Impact velocity of 365 m/s[10].

domain contact force dynamic response for 365 m/s impact speed is highlighted. The trend is almost matching with the reference Methodology[10], with minimum deviation observed which can be attributed to change in the delamination behaviour.

The internal Energy observed by the composite target and the residual kinetic energy is highlighted the Figure 13. It can be observed that for 100m/s and 200 m/s sec the composite material is able to stop the projectile without significant damage and perforation. However, for 300m/s there is significant damage with perforation observed in few layers (Figure 13) and the material is not able to resist the impact force after certain progressive failure.

Also, it can observe that the material starts to delaminate more and penetration of the projectile would be severe after 250 m/s. Energy observed for an impact velocity of 100 m/s and 200 m/s highlights that the Dyneema material can easily withstand the damage and the deformations, thereby making it easier to be deployed for application within this range of velocities.

5.0 Conclusion

The objective of this research was to use LS-DYNA to establish a finite element model to evaluate the delamination effect of DYNEEMA material using *Mat59. The slight deviation in the results when compared with

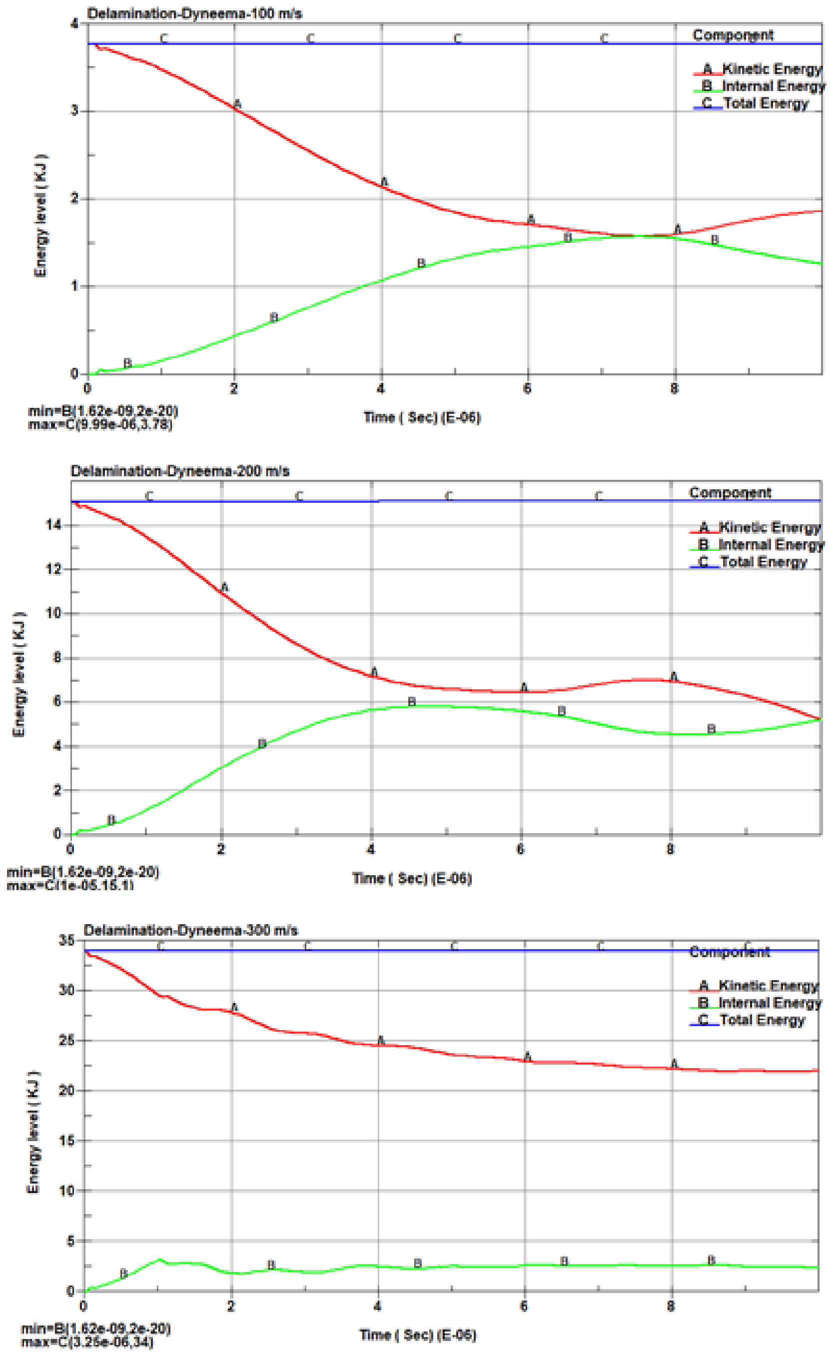


Figure 13. Energy observed of the total system for different Impact velocities.

experimental and *Mat_162 can be attributed to material model. Even though the deviation is small, the current numerical and reference results are in good agreement. Delamination was effectively captured between individual plies; Mode I crack simulations were a suitable way to start checking on the contact tiebreak definition's parameters and ensuring that the results were plausible. Mesh dependency and computing limits were discovered to be the most challenging aspects of the simulation. Also, it was observed that the material started to perforate at higher impact velocities.

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