A numerical analysis of CFRP laminate behaviour under high-velocity impact

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Abstract This work focuses on the numerical investigation of the ballistic and delamination mechanisms of T700 carbon fibre/epoxy laminate with a [0/90]s stacking sequence. The effect of the mass and diameter of spherical projectiles on CFRP laminate is investigated numerically. A numerical study of projectiles with different diameters (6mm, 10 mm, and 12mm) on CFRP laminates with thicknesses of 1.5mm and 3mm is conducted, encompassing a broad spectrum of projectile incident velocities (from 500 m/s to 1700 m/s). Furthermore, a numerical model containing cohesive elements is developed and verified using experimental results from the literature. When compared to experimental results, the numerical simulation results were found to be within acceptable ranges. On comparing the effect of laminate thickness, it was determined that 1.5mm laminates had better energy absorption capability as velocity increased compared to 3mm laminates. The results indicated that the energy absorption capability of the 3mm laminate was reduced by 8.8%, whereas the 1.5mm laminate was reduced by 3%. A study using multi-layered laminate is studied, and a parametric study is carried out with projectiles of different mass and size. The results from the parametric study concluded that smaller geometry projectiles induced more significant damage in the laminate than larger geometry projectiles with constant mass.

Keywords: CFRP, projectile impact, microstructural damage, cohesive elements, numerical model

1 Introduction

CFRP composites have piqued interest in the aerospace and automotive sectors because of their advantageous strength-to-weight ratio, lightweight nature, fuel economy, and outstanding fatigue resistance. The response to impact load of composite materials is complicated and is influenced by several variables, like projectile velocity, shape, laminate layup and properties[1]. Although carbon fibre has several advantages, it exhibits relatively low toughness and impact resistance compared to conventional materials [2]. Consequently, the damage due to impact loads diminishes the strength properties or threatens the structure's integrity [3]. To ensure safe and reliable use of CFRP composites in structural applications, impact resistance is one of the primary concerns and must be addressed.

It is critical to explore the impact response of CFRP composites under various loading circumstances to precisely anticipate their performance under impact loading. Researchers have conducted many investigations to examine the parameters affecting the impact response of CFRP laminates that encompass the arrangement of the laminate layup[4-6], laminate thickness[7], temperature[8], type of projectile[9], and the angle of impact[10]. Sudhir et al. [11] numerically studied variation in velocity and ballistic impact resistance capability of CFRP laminate when impacted by a spherical steel projectile. It was concluded that CFRP laminates showed enhanced impact resistance with $[\pm 45]_n$ stacking sequence. Shimamoto et al. [12]studied high-velocity impact experimentally to determine the effect of velocity, temperature and stacking sequence on the failure behaviour of CFRP composites. They determined that the ply orientation strongly influences the laminate's ballistic performance. Yuan et al. [13]examined the behaviour of a CFRP square plate and beam under impact load, and the findings demonstrate that the square shape specimen exhibits lower perforation resistance than the beam specimen. From the literature, it is evident that many configurations of CFRP composite and parameters influencing the impact performance are investigated, but the performance of a multi-layered arrangement of the laminate remains an open topic of research.

The precision and reliability of numerical simulations have enhanced due to the evolution of numerical techniques and the development of material damage models. In the past, numerical investigations of high-velocity impact were carried out using mesoscale modelling, where the constituents of composite laminates are not modelled explicitly[14]. Jagtap et al.[15] studied different failure modes using 3D solid elements and determined that results from the finite element (FE) tool (LS DYNA) predicted the experimental results with acceptable accuracy. Yashiro et al. [16] studiedthe effect of high velocity impact on deformationsand component separationimpact using smoothed particle hydrodynamics (SPH). The anticipated failure pattern innumerical simulation aligned with those seen on the frontal, rear surfaces and sections below the point of impact in the experiments. Grujicic et al. [17]studied quasi-isotropic CFRP laminates under impact using a meso-scale F.E. model based on continuum damage mechanics. They concluded that the adopted method was effective in estimating the energy required for the fracture of individual layers within the laminate, as well as their inherent strength.

Due to the lack of research on the behaviour of multi-layered composites and their interfaces, it is essential to study available constitutive FE models that can accurately estimate interlaminar response of composite laminate under high-velocity impacts. In this paper, a mesoscale FE model of quasi-isotropic and cross-ply CFRP laminate impacted by a sphere projectile has been investigated numerically. The energy absorption efficiency (EAE) is explored using 100mm x 100mm samples with 1.5mm and 3mm thick laminates. Wang et al.[18]experimental data and the numerical simulations in present study are compared to demonstrate the accuracy of numerical simulation in determining the impact mechanism. After understanding the laminate's impact response, a multilayer protection system is studied and the effect of projectile diameter is investigated.

2 Problem Statement

Because of their superior mechanical characteristics, CFRP composites are of interest in various sectors. But CFRP laminates are easily damaged by impacts, especially when subjected to projectile impacts. As a result, it is necessary to comprehend the performance of CFRP laminates under impact loading and develop reliable models to predict the failure mechanisms of the laminate. To achieve this goal, a numerical model is proposed. The numerical model consisting of T700 carbon fibre/epoxy laminate [0/90]s with 1.5mm and 3mm thickness consisting of 36 and 18 plies is validated with experimental results from

Wang et al.[18]. The mechanical properties utilised are presented in **Table 1**. For all impact scenarios, a spherical projectile with a 6mm diameter was used to determine the impact behaviour of CFRP composite at 600-1500 m/s.

Table 1 Mechanical properties of T700/epoxy laminate for numerical simulation [18, 19]

Property	Unit	Values
Density (ρ)	kg/m^3	1570
Youngs Modulus (E_{11})	GPa	132
Youngs Modulus (E_{22})	GPa	10.3
Youngs Modulus (E_{33})	GPa	10.3
Shear Modulus ($G_{12} = G_{13}$)	GPa	6.5
Shear Modulus (G_{23})	GPa	3.9
$\nu_{21} = \nu_{31}$		0.25
ν_{23}		0.38
X_t	MPa	2100
Y_t	MPa	24
X_c	MPa	1050
S_c	MPa	75
Cohesive Element Properties		
Normal stress (T)	MPa	45.1
Shear stress (S)	MPa	100
Mode-I toughness (G_{IC})	kJ/m^2	0.258
Mode-II toughness (G_{IIC})	kJ/m^2	0.723
Benzeggagh-Kenane law parameter	-	1.75

3 Formulation for Damage Modelling

High-velocity impacts cause significant localised deformation in the targets resulting from high pressure and shock waves. These events are characterised by their dynamic nature, involving small mass and high velocity. In general, when CFRP laminates experience high-velocity impact, the types of damage are (a) intra-laminar damage where fibre and matrix failures are dominant (b) inter-laminar damage where delamination failure is dominant.Impact damage needs to be modelled using failure models including damage initiation and propagation criterion.

3.1 Intra-laminar Damage

In the numerical simulation, the behaviour of CFRP laminates under impact loading, the Chang-Chang damage model (MAT 54) was employed. The Chang-Change failure criterion (brittle failure) accounts for matrix and fibre failures caused by in-plane stresses.The failure flags utilised are expressed in the following equation:

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

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

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

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

Where

e_f , e_c= fibre tension and compression

$e_m e_d$ = matrix tension and compression
σ_{aa}, σ_{bb}= stress in fibre and matrix direction,
σ_{ab} = in-plane shear stress,
X_t, X_c = tensile and compressive stress (longitudinal)
Y_t, Y_c = tensile and compressive stress (transverse)
S_c= shear stress
β = weighting factor for shear term

3.2 Inter-laminar Damage

To model the inter-laminar delamination behaviour in composite laminates at the interface of adjoining layers, cohesive zone elements are utilised. The cohesive zone refers to a boundary that exists between the composite laminates, where there are discontinuities in displacement. Two factors, namely the intrinsic toughness of the interface and the cohesive strength, control the fracture process. These parameters are typically connected by the cohesive constitutive law:

$$\sigma = \sigma_{max} f(\lambda) \quad (5)$$

Where
$f(\lambda)$ = describing the shape of the cohesive law(dimensionless);
σ_{max} = cohesive strength

A damage zone surrounding the crack tip in FRP composites signifies that failure is primarily determined by energy-based standards instead of critical stress or strain-based criteria.

3.3 Energy absorption mechanism

Energy absorption refers to the dissipating energy transferred to a laminate during an impact event. The characteristics of the laminate and the type of impact determine the energy absorption mechanism. For impact on 1.5mm and 3mm projectiles, the energy absorption criteria can be established based on the relation between measured incident (V_{inc}) and residual (V_{res}) velocity.

$$E_{abs} = \frac{1}{2} m \left(V_{inc}^2 - V_{res}^2\right) \quad (6)$$

where,
E_{abs} = Energy absorbed
m = mass
V_{inc} = incident velocity
V_{res} = residual velocity

3.4 Methodology

To study the dynamical behaviours of the CFRP laminate under high velocity impact, simulation was done using commercially available FE tool LS DYNA. To simulated the experimental conditions, the square CFRP laminate was clamped at all the edges. To this end, symmetric condition was utilised and only a quarter of the model was used to save the simulation time. The CFRP laminates were meshed with fully integrated 8-noded solid elements and a biased mesh was created with reasonably fine mesh in the impacting region to ensure convergence. A convergence analysis was performed to ensure accurate results and a mesh size of 0.25 mm in the impacting zone was determined to be optimum, providing the required accuracy with acceptable computational time. The considered mesh size is similar to the mesh size range followed in the literature [22]. The laminate consisted of 36 and 18

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plies for 3mm and 1.5mm laminates, respectively, with one element defining one ply. The projectile was represented using solid elements with rigid body attributes and steel material properties were assigned. The complete FE model of CFRP laminate configuration is shown in **Figure 1**.

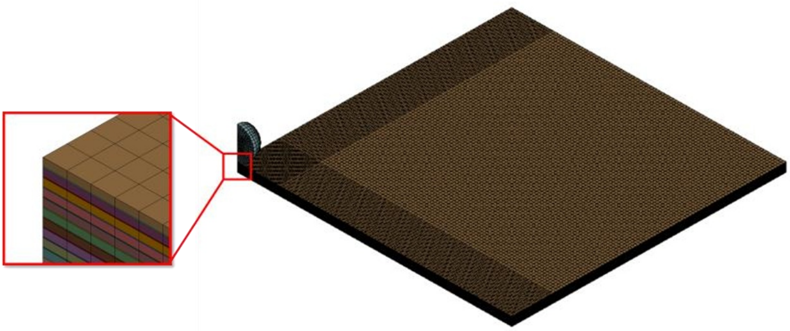

Fig. 1. Finite element model configuration

Recently, discrete crack modelling has been used for high-precision modelling of impact damage in composites. The modelling is accomplished by creating new mesh-independent methods [20] or integrating cohesive elements[21]. Thus, cohesive elements are modelled between each ply in the proposed numerical model, as in **Figure2**.To accurately capture the three-dimensional stress state, the cohesive zone elements shared nodes with the elements of corresponding laminae.

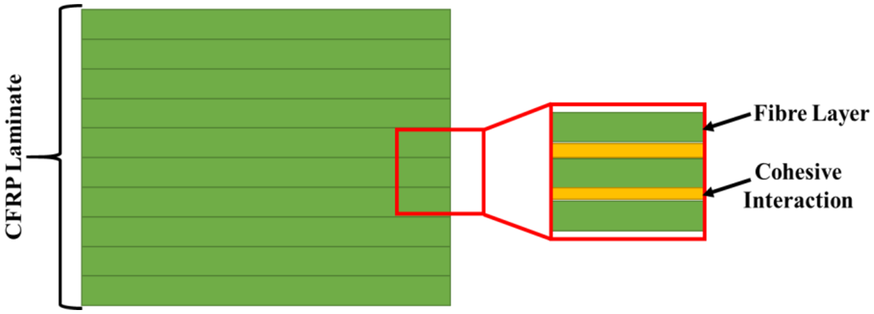

Fig. 2. Modelling cohesive interaction between plies

4 Results and Discussion

In the numerical model, the impact behaviour of CFRP laminates with two thicknesses(1.5mm and 3mm) is studied, and the findings are compared with experimental results in the literature[18]. The ability of the proposed numerical technique to determine the impact performance of CFRP laminates with specified thicknesses at high-velocity impact is discussed.

4.1 Validation based on Residual Velocity

CFRP laminates have poor ductility compared to metal plates, making them inappropriate for energy absorption applications. The efficiency of CFRP laminate as an energy-absorbing structure is investigated numerically to validate the proposed F.E. model. From **Figures 3 and 4**, it is evident that the energy absorption of the laminate is dependent on laminate thickness. The experimental and numerical simulation results in the present work are closer to the results published by Wen et al. [18]. This can be attributed to the fact that the modelling approach in the present numerical study is more detailed, considering the modelling of cohesive layers [25].

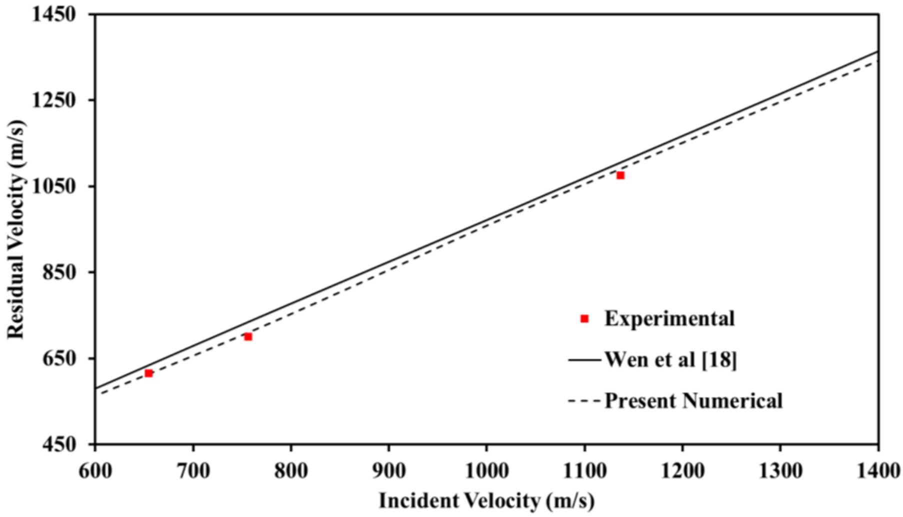

Fig. 3. Residual Velocity comparison for 1.5mm plate

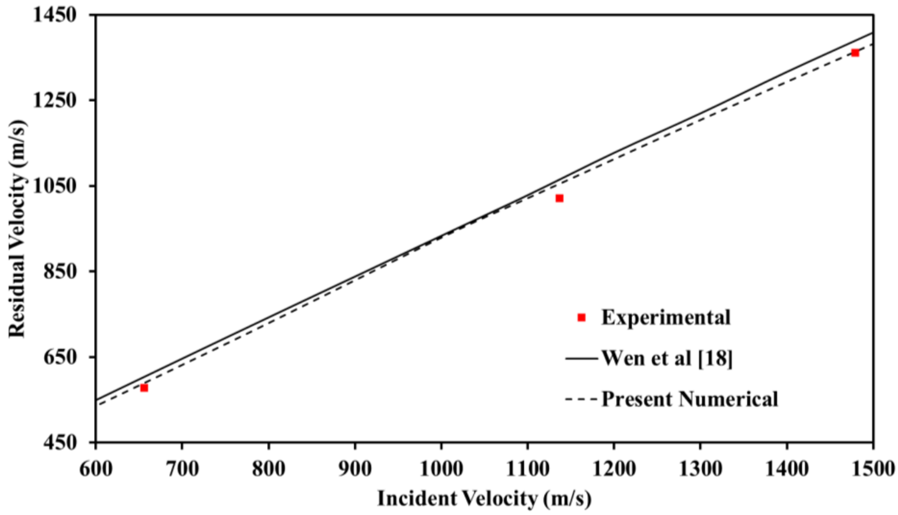

Fig. 4. Residual Velocity comparison for 3mm plate

4.2 Parametric Study

Various projectiles with different dimensions and densities interact with the target during an impact event. Since the dimensions and mass of the projectiles are interconnected, it is difficult to isolate the influence of specific variables on CFRP laminates without influencing other elements. To address this, a parametric study is conducted by altering the dimension or mass of the projectile in the proposed numerical model.

4.2.1 Energy absorption variation with laminate thickness

This section presents the energy absorption efficiency of CFRP laminates with 1.5mm and 3mm thicknesses under particular impact velocity (energy) ranges. **Table 2** and **Table 3** represent 1.5mm and 3mm laminate response to different impact energy under 6mm projectile diameter. From the obtained response of the laminates, it can be observed that at lower velocities, 3mm laminate shows considerably high energy absorption compared to 1.5mm laminate. But as the velocity increases, the energy absorption capability of the laminate 3mm laminate reduces by 8.8%, whereas for 1.5mm laminate, it is reduced by 3% [26].

Table 2 Energy absorption variation at different velocities for 1.5mm laminate

Sl.No.	Incident Velocity (m/s)	Incident Energy(J)	Residual Velocity (m/s)	Residual Energy (J)	Energy Absorbed (%)
1	500	25.00	471.19	22.20	11.19
2	654	42.77	620.12	38.46	10.09
3	750	56.25	713.97	50.98	9.38
4	756	57.15	719.97	51.84	9.30
5	1000	100.00	958.77	91.92	8.08
6	1100	121.00	1055.28	111.36	7.96
7	1136	129.05	1089.49	118.70	8.02
8	1200	144.00	1151.38	132.57	7.94
9	1300	169.00	1246.43	155.36	8.07
10	1400	196.00	1341.48	179.96	8.19

Table 3 Energy absorption variation at different velocities for 3 mm laminate

Sl.No.	Incident Velocity (m/s)	Incident Energy (J)	Residual Velocity (m/s)	Residual Energy (J)	Energy Absorbed (%)
1	500	25.00	439.70	19.33	22.67
2	656	43.03	588.58	34.64	19.50
3	760	57.76	690.26	47.65	17.51
4	1000	100.00	929.56	86.41	13.59
5	1100	121.00	1021.76	104.40	13.72
6	1137	129.28	1055.37	111.38	13.84
7	1200	144.00	1113.10	123.90	13.96
8	1300	169.00	1204.74	145.14	14.12
9	1400	196.00	1293.84	167.40	14.59

4.2.2 Optimise laminate configuration and projectile size effect

Based on results obtained in the energy dissipation mechanism, it was evident that thinner laminates were better energy absorbent than thicker laminate [27]. Thus, multilayer thin CFRP laminates consisting of 1mm thickness were placed 1mm apart (HYB-1) is studied (**Figure 5**). To investigate the impact of projectile dimensions on CFRP laminate damage, parametric studies were carried out using the proposed simulation model. The projectiles used in these studies exhibited varied dimensions (including 6 mm, 10 mm and 12 mm) with different masses. Initial velocity vs residual velocity curves (**Figure 6**) show an increasing trend with increased incident velocity. As the impact velocity increases, two distinct variations in response is observed. Firstly, in the velocity range from 1000m/s to 1100m/s, 10mm and 12mm projectiles show approximately same residual energy. Secondly, for velocity beyond 1100m/s, the distinction between residual velocity is more evident between all three projectiles. This signifies that the projectile diameter is ineffective for a given velocity range, and the material properties of the target material dominate the structural response [28].

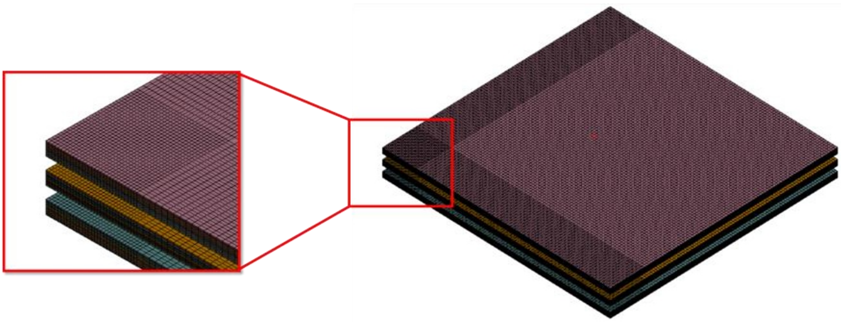

Fig. 5. HYB-1 model description

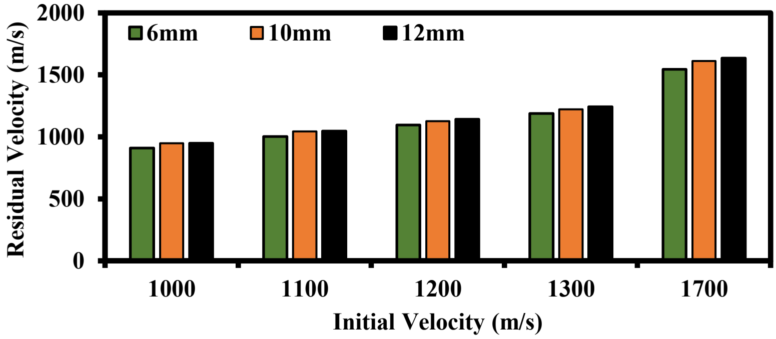

Fig. 6. Effect of projectile diameter on HYB-1 configuration

4.2.3 Influence of projectile dimension with constant mass

Impact events often involve a range of projectiles that differ in size and weight. Understanding the influence of each variable on CFRP laminates is complex because the dimensions and mass of the projectile are interconnected. Researchers conduct parametric studies using a numerical model to avoid interference caused by changing multiple variables simultaneously. In **Figure 7**, the dimensions of the projectile are varied while keeping its mass constant. The contact interface dominates the projectile interaction with CFRP laminate.

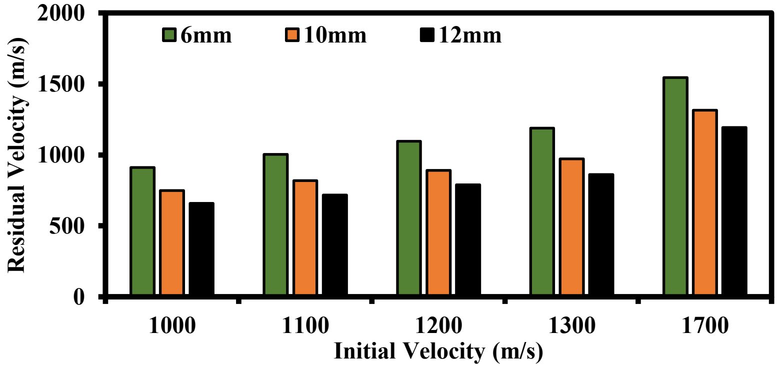

Fig. 7. Effect of projectile diameter with constant mass

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As the projectile diameter increases, contact region is larger between the laminate and projectile leading to greater resistance. It is evident from the result that keeping the mass constant, the smaller projectile resulted in higher residual velocity signifying lower energy absorption. Thus, it can be concluded that 6mm projectiles induced more damage than 10mm and 12mm projectiles. This result conforms with existing literature [23].

4.2.4 Damage Mechanism

It is known that the laminate dissipates the kinetic energy from the projectile as fibre and matrix failures. **Figures 8-10** represent the top and bottom surface failure modes at 1300m/s impact velocity for different laminate configurations. The impact response of CFRP laminates are highly associated with the projectile and laminate mass ratio. The failure modes of CFRP laminate differ with different laminate configurations. For all the studied arrangements, fibre compression was dominant on the top surface, whereas fibre tension mode of failure was dominant on the bottom surface. In the case of matrix failure, both matrix tension and compression were dominant failure modes compared to fibre failure. The failure pattern was similar for 1mm and HYB-1 laminate configuration, where the failures were extended beyond the impact region, signifying higher energy absorption. Whereas in 3mm laminate, the damage modes were localised. Thus, the damage study clearly represents the energy absorption methods the laminate undergoes to resist projectiles at higher velocities.

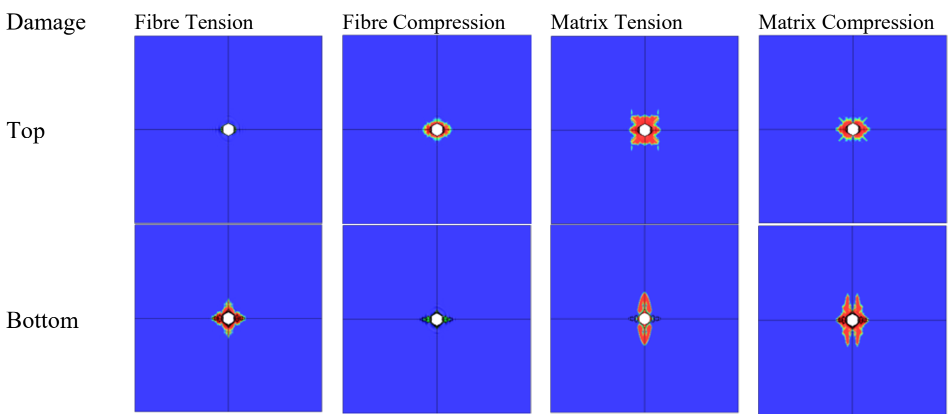

Fig 8. Microstructural damage prediction for 1.5mm laminate under 1300 m/s impact velocity.

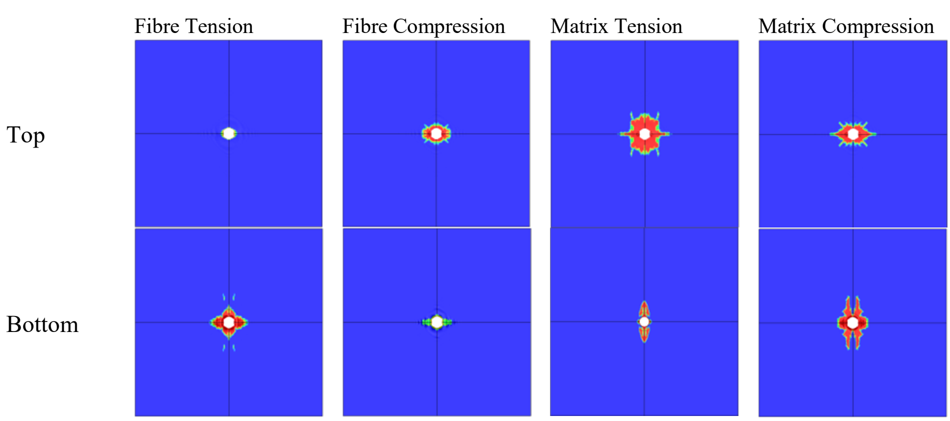

Fig 9. Microstructural damage prediction for 3 mm laminate under 1300 m/s impact velocity.

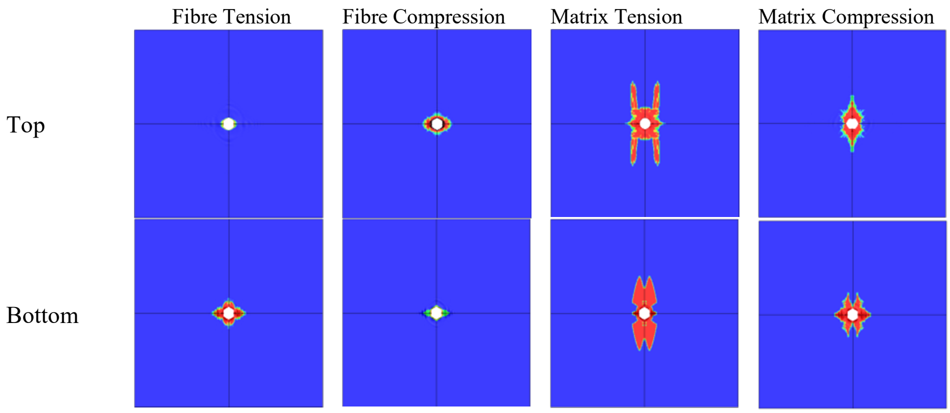

Fig 10. Microstructural damage prediction for HYB-1 laminate under 1300 m/s impact velocity.

5 Conclusion

In this work, projectile impacts at velocities ranging from 500 m/s to 1700 m/s are used to test the dynamic response and damage behaviour of CFRP laminates. The impacts were performed using spherical projectiles with different masses and diameter. To investigate the projectile configuration and damage process of the CFRP laminate, a FE simulation model is presented. The following conclusions are made given the context of the simulation's results:

- As the velocity increases, the ratio of resistance capability of thicker laminates was lower compared to thinner laminates at lower velocities.
- Based on the observation, a Multi-layered CFRP laminate (HYB-1) configuration with thin laminates were studied and compared with performance of monolithic thick laminate. The HYB-1 configuration performed better at higher velocity than 3mm monolithic laminate.
- Projectile mass and diameter have distinct effects on the impact behaviour of the CFRP laminate. A larger size projectile with the same mass compared to a smaller projectile will result in more significant deflection and contact area, resulting in lower residual velocity.

The results may provide useful information for the impact resistance design of composite constructions. and further optimisation study can be conducted to evaluate different thin laminate configurations for better impact-resistant systems.

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