Simulation of high velocity impact test on GFRP

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Abstract. The fundamental requirement in different applications of composites is resistance to high velocity impact loading. The present study is about simulating and investigating high velocity impact tests on E-glass/epoxy composite. The modelling of the composite plate and the projectile is done using Ansys Composite Prepost. The material used for the projectile is mild steel. The impact tests were simulated in Ansys Explicit Dynamics with hemispherical nose configuration and compared with results obtained from experiments done by previous work. Additional simulations were carried out using conical and cylindrical nose configurations. The ballistic limit of the composite is also obtained in each of these cases. Different aspects of the impact mechanism such as formation of cone on the back face of the target, distribution of stress on both the faces were investigated. The impact tests were carried out in previous works using gas gun method where a compressed gas gun bullet is used to penetrate the target. It is concluded that the simulated results had a good agreement with the experiments.

1. Introduction
Composites are extensively used as materials for protective structures. These structures are subjected to high velocity impacts when an object undergoes impact with them. Naik et al [2] analysed the influence of various parameters such as the geometry and material properties of the target, the mass, velocity and configuration of the projectile. The target material was E-glass epoxy and T300 carbon/epoxy composite which was impacted with a flat nosed cylindrical projectile. Soydan et al [3] experimentally investigated ballistic impacts on targets with three different layers of material namely fibre-cement, Kevlar fabric and steel. The simulated results obtained using Ansys Explicit Dynamics were in good agreement with those of the experiments. Onyechi et al [4] conducted ballistic impact tests on GFRP composites using conical and ogival projectiles. It was observed that the ballistic limit were almost the same for both conical and ogival projectiles though the conical projectiles were to be having a higher penetration effect than the ogival ones. Silva et al [5] performed ballistic tests on Kevlar 29/Vyniliester laminates and a numerical model was developed to calculate the limit perforation velocity. Rajput et al [6] simulated the impact of a spherical projectile on Kevlar 129 helmets using Finite Element Method and validated results from previous literature.

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Jin et al [7] studied the damage caused due to ballistic impacts on bi-axial warp knitted composites both experimentally and by FEM simulation. The mechanism of failure and energy absorption was investigated by calculating the residual velocities. Ramadhan et al [8] performed high velocity impact tests on Kevlar 29 and aluminium and predicted the ballistic limit using numerical parametric studies. It was also concluded that the energy absorption increases as the initial velocity increases. Bresciani et al [9] numerically modelled the impact of tungsten projectiles on Kevlar 29 with epoxy matrix. There were two different models one of which considers the plates to be homogenous and in the other the yarns are reproduced individually. Banerjee et al [10] studied the impact of ogival projectiles moving at ordnance velocities on steel armours by numerical methods. Infanta et al [1] studied high velocity impacts on Glass Fibre Reinforced Polymer using gas gun method and the energy absorption levels during these impact tests were estimated. This work forms the basis of the studies done in the present paper. The objective of the present work is to present a simulation model for the high velocity impact on the target material for three different nose configurations. The target material used is bi-axial glass fibre composite with epoxy resin and the projectile material used is mild steel. The software used for this work is ANSYS 2019 R3. For composite modelling ANSYS Composite Prepost (ACP) is used. The impact test is simulated using Explicit Dynamics module in ANSYS Workbench.

2. Material Properties
The composite material is bi-axial glass fibre reinforced polymer. The resin used is Bisphenol-A-based epoxy resin. The composite is fabricated using a process called Vacuum Assisted Resin Transfer Molding (VARTM). The process involves the use of a vacuum to facilitate resin flow into a fibre layup contained within a mold tool covered by a vacuum bag. A lamina is the building block of modern composite laminated structures. Each lamina may have in itself have more than one types of fibres. These fibres may be oriented in different directions. Each lamina may have a different thickness, fiber material, matrix material and fibre orientation angle. A lamina is also known as a ply, or a layer. The material used here has a ply angle of 45 degrees and 8 plies in total. There are 4 layers with each layer having 2 plies totalling up to 8 plies. The properties of Epoxy E-glass and mild steel is given in table 1 and table 2 respectively

| Property                        | Value | Unit |
|---------------------------------|-------|------|
| Density                         | 2000  | kg/m³|
| Young's Modulus (X)             | 4.50E+10 | Pa   |
| Young's Modulus (Y)             | 1.00E+10 | Pa   |
| Young's Modulus (Z)             | 1.00E+10 | Pa   |
| Poisson's ratio (XY)            | 0.3   |      |
| Poisson's ratio (YZ)            | 0.4   |      |
| Poisson's ratio (XZ)            | 0.3   |      |
| Shear Modulus (XY)              | 5.00E+09 | Pa   |
| Shear Modulus (YZ)              | 3.85E+09 | Pa   |
| Shear Modulus (XZ)              | 5.00E+09 | Pa   |
| Tensile Stress Limit (X)        | 1.10E+09 | Pa   |
| Tensile Stress Limit (Y)        | 3.50E+07 | Pa   |
| Tensile Stress Limit (Z)        | 3.50E+07 | Pa   |
| Compressive Stress Limit (X)    | -6.75E+08 | Pa   |
| Compressive Stress Limit (Y)    | -1.20E+08 | Pa   |
| Compressive Stress Limit (Z)    | -1.20E+08 | Pa   |
Table 2. Bullet Properties of Mild Steel (Engineering Data).

| Property                  | Value   | Unit   |
|---------------------------|---------|--------|
| Density                   | 7850    | kg/m³  |
| Young's Modulus           | 2.00E+11| Pa     |
| Poisson's ratio           | 0.3     |        |
| Bulk Modulus              | 1.67E+11| Pa     |
| Shear Modulus             | 7.69E+10| Pa     |
| Tensile Yield Strength    | 2.50E+08| Pa     |
| Compressive Yield Strength| 2.50E+08| Pa     |
| Tensile Ultimate Strength | 4.60E+08| Pa     |
| Compressive Ultimate Strength| 0.00E+00| Pa     |

Table 3. Plate Properties.

| Property       | Value   | Unit   |
|----------------|---------|--------|
| Plate Dimension| 0.150x0.150 | m²     |
| Specimen thickness | 2x10⁻³  | m      |
| Fiber Material  | E-glass | -      |
| Matrix Material | Epoxy resin | -   |
| Layer thickness | 0.5x10⁻³ | m      |
| Ply thickness   | 0.25x10⁻³| m      |

Table 4. Bullet Properties.

| Rod length           | Diameter    | Material   | Cone angle |
|----------------------|-------------|------------|------------|
| Hemispherical        | 1.5x10⁻²m   | 9.8x10⁻³m | Mild Steel | -         |
| Conical              | 1.5x10⁻²m   | 9.8x10⁻³m | Mild Steel | 60°       |
| Cylindrical          | 1.5x10⁻²m   | 9.8x10⁻³m | Mild Steel | -         |

3. Composite Modelling using ACP

Ansys Composite Prepost has a specialized module for designing composite models. The materials to be used in the simulation are first assigned in Engineering Data where the database for all materials is available. Epoxy E-Glass and mild steel are obtained from this database. The geometry of the plate and the bullet is designed in Ansys Design Modeller. The completed geometry is shown in the figure 1.
The meshing method and the mesh type are entered in Model. The meshing method is multizone method and the mesh type is hexa. The model is shown in figure 2 and figure 3.

Table 5. Orientation of each ply group along with material.

| Fabric       | Angle |
|--------------|-------|
| Epoxy E-glass| -45   |
| Epoxy E-glass|  45   |
| Epoxy E-glass| -45   |
| Epoxy E-glass|  45   |
| Epoxy E-glass| -45   |
| Epoxy E-glass|  45   |
| Epoxy E-glass| -45   |
| Epoxy E-glass|  45   |

All the plies are made into a stackup before moving forward with analysis. Every ply has 0.25mm thickness and a 45 degree angle of fibre orientation. This has been illustrated in figure 4 and figure 5.
The model must be analysed in Explicit Dynamics for simulating the high velocity impact test. The figure below shows the project schematic and the workflow between ACP and Explicit Dynamics. The connection and relationship is shown in figure 6.

4. Simulation
According to the project schematic since the model and geometry of ACP and Explicit Dynamics are linked together the model need not be made and defined in Explicit Dynamics once again. The Global Coordinate System is chosen and the initial conditions are given in table 4 and table 5. The bullet velocity assigned is 145m/s. Fixed support must also be provided to all 4 edges of the plate. The solution of unknown parameters are also assigned. Three main types of solutions are obtained. Total Deformation provides the deformation occurring in different areas of the plate and the bullet before and during the impact. Equivalent Stress shows the stress distribution during the impact. Directional velocity provides the information regarding residual velocity of the bullet.

5. Results and Analysis
The simulation was carried out for all velocities above 50m/s till the ballistic limit is reached. The resin and the fibre are considered to be a single entity according to equivalent single layer theory. Therefore the resin thickness would not be significant in the obtained results though the properties of the resin would be incorporated into the properties of the plate.

5.1. Total deformation
Figure 7. Deformation of the plate during impact and formation of cone (Hemispherical Bullet).

Figure 8. Deformation of plate during impact and formation of cone (Cylindrical Bullet).
5.2. Directional velocity

During impact if the total kinetic energy of the projectile is not dissipated the projectile would have some value of velocity after penetration. The ballistic limit velocity is the velocity at which the bullet is able to fully penetrate into the material. The ballistic limit was found to be close to 251m/s for hemispherical bullet, 237m/s for cylindrical bullet and 244m/s for conical bullet. We can see that conical bullet doesn’t fully deform/penetrate the material at 243m/s but does so at 244m/s. Cylindrical Bullet doesn’t fully deform the material at 236m/s but does so at 237m/s. Hemispherical bullet also doesn’t deform the material fully at 250m/s but does so at 251m/s.

**Figure 9.** Deformation of plate during impact and formation of cone (Conical Bullet).

The experimental observations showed a cone formation on the back of the composite plate at the ballistic limit. The cone formation on the back of the target is one of the many possible energy absorbing mechanisms. The stress incurred on the point determines the extent up to which the target undergoes deformation.

**Figure 10.** Ballistic velocity of conical bullet.
Figure 11. Deformation for conical bullet at 243m/s.

Figure 12. Deformation for conical bullet at 244m/s.

Figure 13. Ballistic velocity of cylindrical bullet.

Figure 14. Deformation for cylindrical bullet at 237m/s.

Figure 15. Deformation for cylindrical bullet at 236m/s.

Figure 16. Ballistic velocity for hemispherical bullet.
5.3. Equivalent stress

After the impact the stresses were mainly concentrated in two specific regions. The maximum stress incurred was found to be 511.4 MPa and the minimum to be 0 MPa. It was found out to be 218.63 MPa and minimum of 0 MPa for Conical Bullet and 372.47 MPa (maximum) and 0.5427 MPa (minimum) for Cylindrical shaped bullet. However the distribution did not deviate from the centre portion of the plate implying that the peripheral regions remain unaffected due to the impact of the bullet.

**Figure 17.** Deformation for hemispherical bullet at 251 m/s.

**Figure 18.** Deformation for hemispherical bullet at 250 m/s.

**Figure 19.** Stress distribution of the plate during impact by hemispherical shaped bullet.

**Figure 20.** Stress distribution of the plate during impact by cylindrical shaped bullet.
Figure 21. Stress distribution of the plate during impact by conical shaped bullet.

6. Verification
The experimental observations are as follows. Impact test was performed using gas-gun method. The set-up for the impact test also consists of a data acquisition system combined with a high speed camera and display unit to measure the time response of the bullet penetrating the panel and also to measure the velocity of the bullet. The schematic representation of the impact test rig (gas-gun method) is shown below \cite{1}. However experimental validation was done only for hemispherical configuration of projectile.

![Schematic of the experimental setup.](image)

7. Conclusions
The hemispherical bullet was made to hit the target with an impact velocity of 140–150 m/s at the time of strike. The kinetic energy absorbed by the plate is given by the equation: Kinetic energy absorbed = 0.5 m (v_i^2 – v_r^2) where m is the mass of the projectile and v_i and v_r are initial and residual velocities. The residual velocity for an impact velocity of 145m/s was found out to be 106m/s. The experimental residual velocity is in good agreement with the simulated value which is 105.39m/s. The energy absorbed in this case would be 39J. The absolute error is 0.39m/s. The simulated results of the cylindrical configuration are verified with the reported experimental results \cite{1}. Among the three projectile configurations the hemispherical configuration has the highest ballistic limit while the lowest was that of cylindrical.
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