5.1 Assumptions

As terminal ballistics is a very complex phenomenon, in the current study various assumptions have been made to simplify the problem. Here we have listed the following assumptions:

1. As no exact solution exists for the ballistics problem, we have to rely on empirical equations that fit into the situation. In the current study we have used the Johnson–Cook (JC) constitutive model to consider the high strain rate behaviour of the material. The strain rate hardening effects and thermal softening are integrated in the unified JC model [61].

2. The Lagrangian scheme is more efficient for the problem considered here, since the grid is only embedded into the penetrator and the target. To solve the penetration of a thick target, however, a Lagrangian material should erode and the element essentially disappears although the mass is retained at the nodes [61].

3. Even though temperature plays a role in deciding the properties of the materials at high velocities and strain rates, we have analyzed the problem without considering the effect of temperature due to the inability of the software to handle this.

4. The main limitations of a Lagrangian formulation for large deformation studies (such as those occurring in ballistic penetration) is the excessive distortion of the elements, which leads to unacceptably small time steps and numerical instability of the solution. Hence the distorted elements are generally eroded using criterion such as a critical value of the equivalent plastic strain. The critical value of the equivalent plastic strain used for erosion is chosen such that the result approaches the limit where only the inverted elements are deleted for the Lagrangian codes. This generally occurs for values of equivalent plastic strain larger than 2.0. Hence a failure plastic strain value of 2.0 is used throughout the simulation.
5. An explicit contact/friction algorithm is used to represent contact between deformable bodies.

6. A constant coefficient of friction is maintained throughout the analysis.

7. No failure criterion is considered in the analysis. It should be noted that in Lagrangian formulations, the elements are eroded at smaller values of the equivalent plastic strain to incorporate material failure mechanisms in the computational simulations.

   Adaptive re-meshing algorithm is not used, which could increase the accuracy of the analysis by reducing the maximum distortion in the elements.

**Parameters considered:**

For Monolithic penetrator:

\[
L = \text{Total length of the penetrator (mm)}
\]
\[
D = \text{Diameter of the penetrator (mm) } = 10 \text{ mm (constant)}
\]

For Segmented penetrator:

\[
L = \text{Length of each segment (mm)}
\]
\[
S = \text{Spacer length (mm)}
\]
\[
D = \text{Diameter (mm)}
\]
\[
L_{\text{coll}} = \text{Collapsed length (mm)}
\]
\[
P = \text{Depth of penetration (mm)}
\]

### 5.2 Constitutive model and Material data

Based on the assumption made in the earlier section and the literature review, the JC constitutive model was used for our analysis using PAMCRASH. So as to consider the JC constitutive model in our analysis, material type-16, namely “Elastic-Plastic Solid with damage failure”, was chosen to define the material constants. In the above-chosen material type the parameter for the power law and the strain rate hardening part of the JC model was input separately. The power law as defined in the material type is given by equation 5-1
\[ \sigma = a + b\varepsilon^n \] 5-1

where ‘a’ is the yield strength (MPa), ‘b’ is the hardening modulus (MPa), n is the hardening coefficient and \( \varepsilon_p \) is the effective plastic strain.

Then the JC law is given by

\[ \sigma_n = \sigma_y \left[ 1 + \frac{1}{p} \ln \left( \max \left( \frac{\dot{\varepsilon}}{D}, 1 \right) \right) \right] \] 5-2

where

- \( p \) is the strain rate sensitivity coefficient,
- \( D \) is the reference strain rate (S^{-1}).

Based on the power law and the strain hardening law the material data was obtained from the literature [61, 63] as given in Table 5.1.

Table 5.1: Parameters of the Johnson-Cook constitutive equation

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cc)</th>
<th>a  (GPa)</th>
<th>b  (GPa)</th>
<th>n</th>
<th>p</th>
<th>D (S^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.870</td>
<td>0.75</td>
<td>1.15</td>
<td>0.49</td>
<td>83.33</td>
<td>1000</td>
</tr>
<tr>
<td>Tungsten Carbide</td>
<td>17.580</td>
<td>1.07</td>
<td>0.165</td>
<td>0.11</td>
<td>357.14</td>
<td>1000</td>
</tr>
</tbody>
</table>

The simulations were performed at an impact velocity of 1500 m/s using a cylindrical tungsten carbide penetrator with a flat nose, with length to diameter ratio (L/D) of 1, 2, 4, 6, and 8 and spacer length to diameter ratio (S/D) of 1, 2, 4, 6, and 8. The target was made of steel block of dimensions, 100mm in length, width and height. The relevant mechanical constants and the JC parameters for the two materials are summarized in Table 5.1. Both projectile and the target were modelled as an
elastic–plastic solid with damage failure material using Material Type 16 in PAMCRASH.

The penetrator was meshed using 6-node penta 3D elements with one integration point and stiffness-based hourglass control and the target was meshed using hexahedral solid elements. The contact between the projectile and the target was modelled using a self-impacting node to segment contact type with edge treatment available in PAMCRASH as Type 36. Frictional effects were considered and a constant value of the coefficient of friction, 0.2, was maintained throughout the simulations.

In order to reduce the computational time, which is affected by both the element size and the total number of elements, the mesh in the global part was done optimally in order to obtain fairly accurate results. The mesh density for the target is 8 elements per cubic centimetre. For this mesh density, the initial size of the element in the local region is 5mm x 5mm x 5mm, and the total number of elements in the target plate is 8000. A finer mesh was chosen for the penetrator, which had an initial element length of 10mm, indicating a total number of 30 elements per segment.

5.3 Modelling and Pre-processing

5.3.1 Solid Modelling:

To create the penetrator part in CATIA, first in sketcher mode, a circle of the desired diameter (10mm) was drawn and suitable constraints and dimensions were given. Then, using the Part Design mode and the Pad command, the circle was extruded from a 2D surface to a 3D solid. The extrusion was done for a length of 1000mm. This way, we created a template from which all the segmented and monolithic penetrators were generated. The file was exported to Visual Mesh by way of saving it as an IGES file (to ensure no errors) as shown in Fig. 5.1.
5.3.2 Meshing:

The CAD model of the cylindrical penetrator was imported into Visual Mesh. This had a diameter of 10mm. The top circular surface of the cylinder was meshed using triangular elements. Then, this surface mesh was converted to a solid mesh of penta elements, which spanned throughout the penetrator’s length. The solid mesh consisted of 30 penta elements per segment, each of 10mm length.

The target was generated directly in Visual Mesh with dimensions 100mm x 100mm x 100mm. The solid mesh consisted of 8000 hex elements spanning throughout its body. In both the models, the mesh created was relatively fine such that accurate results can be obtained in the solution stage as given in Fig.5.2 (a), (b) and (c).

Fig.5.2: (a) Solid model of penetrator (b) Meshed penetrator model (c) Penetrator and Target
5.3.3 Data Input

The meshed models were imported into Visual CRASH-PAM. Material types and their mechanical properties were input for the penetrator and the target. For the penetrator, the material assigned was steel and for the target, the material assigned was tungsten carbide. Mechanical properties and JC parameters were input separately for the penetrator and the target. The initial linear velocity of the penetrator was defined and the target was kept fixed along its edges in the form of displacement boundary conditions. The edges were rigidly constrained in X, Y and Z directions such that no motion of the constituent nodes was possible. A self-impacting node to segment contact type with edge treatment was then defined for the penetrator and the target. This was to ensure that an interaction between the penetrator and target is faithfully transmitted into the software, thus, mimicking a real experimental study. The number of frames in which the simulation will be viewed is specified by inputting the time steps in which an output from the software during the simulation is required. All the simulations were run with a run-end time of 0.002 sec or more, so that the complete penetration of the projectile is simulated. Frames were generated and the key parameters were evaluated at regular time intervals shown in Fig. 5.3(a–b).
5.4 Solver and Post-Processing

5.4.1 Solver

The pre-processed file saved in a solver readable format and submitted to the solver. The solver generated at each time step, details regarding the element number that is being solved, the part to which the element belongs, type of element (shell, solid, etc.), the global kinetic energy, internal energy and total energy are summarized after each cycle as shown in Fig.5.4.

After the completion of the solution cycles, details on the number of cycles, CPU time, elapsed time and their ratio as a percentage were displayed. Then, a post-processor readable file was generated.

5.4.2 Post-processing

The solver output file is opened in Visual Viewer and after selecting a suitable view. The von Mises stress – time and the equivalent plastic strain – time dynamic contours were also invoked and viewed. The frames having the maximum von Mises stress and equivalent plastic strain contours and their values were saved as screenshots for later viewing and analysis. Important parameters such as maximum displacement of the target nodes (penetration depth), kinetic energy, potential energy and total energy were quantified in terms of their evolution over time by plotting the corresponding graphs.
5.5 Results and Analysis

5.5.1 Penetrator parameters

Detailed investigations for the various specifications of the penetrator (L/D and S/D ratios) were conducted. For monolithic penetrators, considered the cases, where L/D=3, 6, 12, 18 and 25. In segmented penetrators, L/D ratios of 1, 2, 4, 6 and 8 were considered. For each L/D ratio, S/D ratios of 1, 2, 4, 6 and 8 were taken. Therefore, total of 25 analysis for segmented penetrators and 5 analyses for monolithic penetrators are conducted. The results show plots of the different parameters like displacement, plastic strain, energy (internal, kinetic, and total) and the von Mises stresses acting on the faces. The plots encompass a wide method of representations, from contour plots to the basic parameter v/s time plots. The depth of penetration obtained for all possible combinations of L/D ratio and S/D ratios is given in Table 5.2.
Table 5.2: Penetration depth and P/L_{col} for various L/D and S/D ratios for segmented and monolithic penetrators.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Penetrator</th>
<th>L/D</th>
<th>S/D</th>
<th>Depth of Penetration (P) mm</th>
<th>Collapsed Length (L_{col}) mm</th>
<th>P/ L_{col}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Monolithic</td>
<td>3</td>
<td></td>
<td>17.3</td>
<td>30</td>
<td>0.576</td>
</tr>
<tr>
<td>2.</td>
<td>Monolithic</td>
<td>6</td>
<td></td>
<td>22.4</td>
<td>60</td>
<td>0.373</td>
</tr>
<tr>
<td>3.</td>
<td>Monolithic</td>
<td>12</td>
<td></td>
<td>26.2</td>
<td>120</td>
<td>0.218</td>
</tr>
<tr>
<td>4.</td>
<td>Monolithic</td>
<td>18</td>
<td></td>
<td>28</td>
<td>180</td>
<td>0.155</td>
</tr>
<tr>
<td>5.</td>
<td>Monolithic</td>
<td>24</td>
<td></td>
<td>28.75</td>
<td>240</td>
<td>0.119</td>
</tr>
<tr>
<td>6.</td>
<td>Segmented</td>
<td>1</td>
<td>1</td>
<td>17.59</td>
<td>30</td>
<td>0.586</td>
</tr>
<tr>
<td>7.</td>
<td>Segmented</td>
<td>2</td>
<td>18</td>
<td>30</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Segmented</td>
<td>4</td>
<td>17.72</td>
<td>30</td>
<td>0.590</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Segmented</td>
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<td>17.45</td>
<td>30</td>
<td>0.581</td>
<td></td>
</tr>
<tr>
<td>10.</td>
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<td>8</td>
<td>18</td>
<td>30</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Segmented</td>
<td>2</td>
<td>21.81</td>
<td>30</td>
<td>0.363</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Segmented</td>
<td>2</td>
<td>21.09</td>
<td>30</td>
<td>0.351</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Segmented</td>
<td>4</td>
<td>20.54</td>
<td>30</td>
<td>0.342</td>
<td></td>
</tr>
<tr>
<td>14.</td>
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<td>6</td>
<td>20.18</td>
<td>30</td>
<td>0.336</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Segmented</td>
<td>8</td>
<td>20.72</td>
<td>30</td>
<td>0.345</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Segmented</td>
<td>4</td>
<td>1 25.9</td>
<td>120</td>
<td>0.216</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Segmented</td>
<td>2</td>
<td>25.8</td>
<td>120</td>
<td>0.206</td>
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</tr>
<tr>
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<td>25.06</td>
<td>120</td>
<td>0.208</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>Segmented</td>
<td>6</td>
<td>23.63</td>
<td>120</td>
<td>0.197</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>Segmented</td>
<td>8</td>
<td>25.53</td>
<td>120</td>
<td>0.204</td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>Segmented</td>
<td>6</td>
<td>27.72</td>
<td>180</td>
<td>0.154</td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>Segmented</td>
<td>2</td>
<td>26.81</td>
<td>180</td>
<td>0.149</td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>Segmented</td>
<td>4</td>
<td>26.13</td>
<td>180</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>24.</td>
<td>Segmented</td>
<td>6</td>
<td>26.13</td>
<td>180</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>Segmented</td>
<td>8</td>
<td>26.59</td>
<td>180</td>
<td>0.147</td>
<td></td>
</tr>
<tr>
<td>26.</td>
<td>Segmented</td>
<td>8</td>
<td>28.18</td>
<td>240</td>
<td>0.117</td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>Segmented</td>
<td>2</td>
<td>28.18</td>
<td>240</td>
<td>0.117</td>
<td></td>
</tr>
<tr>
<td>28.</td>
<td>Segmented</td>
<td>4</td>
<td>27.5</td>
<td>240</td>
<td>0.115</td>
<td></td>
</tr>
<tr>
<td>29.</td>
<td>Segmented</td>
<td>6</td>
<td>27.95</td>
<td>240</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>30.</td>
<td>Segmented</td>
<td>8</td>
<td>28.64</td>
<td>240</td>
<td>0.119</td>
<td></td>
</tr>
</tbody>
</table>
5.6: Comparison of segmented (L/D=1) and equivalent monolithic (L/D=3) penetrator

Fig. 5.6 shows contour plots of von Mises stress for different cases of segmented / diameter of segmented penetrator.

5.6.1 von Mises Stress Comparison

Fig 5.6: von Mises Stress distribution contour plots for different S/D ratios

Fig 5.7: Equivalent Plastic Strain Contour plots for different cases of S/D
Fig. 5.7 shows the contour plots of plastic stain for different cases of space/diameter of the segmented penetrator.

### 5.6.3 Displacement Comparisons

Fig. 5.8 shows the displacement path for different cases of S/D ratio of the segmented penetrator.

![Displacement plots for different cases of S/D](image)

**Fig. 5.8:** Displacement plots for different cases of S/D

### 5.6.4 Energy Comparisons

![Energy plots for different cases of S/D](image)

**Fig. 5.9:** Energy plots for different cases of S/D
5.6.5 Discussion

From the stress and strain contour plots (Fig. 5.6–5.10), it is seen that there is a large magnitude of stress at the tip of the penetrator; this is basically due to impact on the target. Comparatively, the spacer material, which is weaker, has less magnitude of stress induced so it is easily strained. As the target is constitutionally weaker than the penetrator, it easily undergoes deformation with less magnitude of stress. Hence as we move away from the point of impact, the stress bands of decreasing magnitude can be seen. Also it can be seen that even though the target is huge, a very small region around the point of impact is strained but the stress wave propagates throughout the material.

From the displacement plots it can be inferred that as the S/D ratio (= 1, 2) increases, the depth of penetration increases to a value of 18mm. The depth of penetration decreases for S/D ratios (= 4, 6). For the remaining S/D ratio it again increases. This can be explained as follows: as initially S/D is small, the time for it to get eroded is less and this gives the segments greater energy to impact the target. However, as spacer length S/D (= 4, 6) increases, a large time is taken to erode the spacers and energy is lost during this stage: hence P/L and P drop. For the case of S/D (= 8) due to very long length of the penetrator, the depth of penetration increases. But it is impractical to use long penetrators as a large amount of initial KE is required to launch the penetrator.

Fig. 5.10 Penetration depth /collapsed length (P/L) vs. S/D for segmented penetrator of L/D ratio = 1
The initial kinetic energy goes on increasing with the increase in the size of the model governed by the equation \( KE = \frac{1}{2} mV^2 \). As the S/D increases, a greater amount of initial KE is possessed by the projectile and thus time for this energy to reduce to constant value also increases. For S/D = 1 \( KE = 58 \, e+9 \, kg \, mm^2/s^2 \) and it takes approx 50 \( \mu s \) to fall to zero. This indicates that power transmitted is 1.16\(+15 \, kgmm^2/s^3 \) or 1.16 MW. Similarly for the other cases the rate of energy transfer is found to be 1.15, 1.198, 1.11, 1.1545 and 1.10 MW for S/D = 0, 2, 4, 6 and 8, respectively.

5.7 Comparison of segmented (L/D=2) and equivalent monolithic (L/D=6) penetrator

5.7.1 von Mises Stress Comparison

![Fig.5.11: von Mises Stress Contour plots for different cases of S/D](image-url)
5.7.2 Equivalent Plastic Strain

Fig. 5.12: Plastic Strain Contour plots for different cases of S/D

5.7.3 Displacement Comparisons

Fig. 5.13: Displacement plots for different cases of S/D
5.7.4 Energy Comparisons

Fig. 5.14: Energy plots for different cases of S/D

5.7.5 Discussion

From the stress and strain contour plots (Fig. 5.11–5.15), it is seen that there is a large magnitude of stress at the tip of the penetrator; this is basically due to impact on the target. Comparatively, the spacer material, which is weaker, has less magnitude of stress induced so it is easily strained. As the target is constitutionally weaker than the penetrator, it easily undergoes deformation with less magnitude of stress. Hence as we move away from the point of impact, the stress bands of decreasing magnitude can be seen. Also it can be seen that even though the target is...
huge, a very small region around the point of impact is strained but the stress wave propagates throughout the material.

From the displacement plots it can be inferred that as the S/D ratio (= 1, 2, 4, 6) increases, the depth of penetration is decreases to a value of 20.2 mm. subsequently the depth of penetration increases for S/D ratio (= 8). This can be explained as follows: as spacer length S/D increases, a large time is taken to erode the spacers and energy is lost during this stage: hence P/L and P drop. For the case of S/D (= 8) due to very long length of the penetrator, the depth of penetration increases. But once again it is impractical to use long penetrators as a large amount of initial KE is required to launch the penetrator.

The initial kinetic energy goes on increasing with the increase in the size of the model governed by the equation KE= 1/2 mV^2. As the S/D increases, a greater amount of initial KE is possessed by the projectile and thus time for this energy to reduce to constant value also increases. For S/D= 1 KE = 105 e+9 kg mm^2/s^2 and it takes approx 80 µs to fall to zero. This indicates that power transmitted is 1.31e+15 kgmm^2/s^3 or 1.31 MW. Similarly for the other cases the rate of energy transfer was found to be 1.5, 1.31, 1.53, 1.3, 1.307 and 1.25 MW for S/D = 0, 1, 2, 4, 6 and 8, respectively.

5.8 Comparison of segmented (L/D=4) and equivalent monolithic (L/D=12) penetrator

5.8.1 von Mises Stress Comparison

Fig.5.16: von Mises Stress plots for different cases of S/D
### 5.8.2 Equivalent Plastic Strain Comparisons

![Plastic Strain plots for different cases of S/D](image)

**Fig 5.17:** Plastic Strain plots for different cases of S/D

### 5.8.3 Displacement Comparisons [L/D = 12 (mono), L/D = 4 (Segmented)]

![Displacement plots for different cases of S/D](image)

**Fig 5.18:** Displacement plots for different cases of S/D
5.8.4 Energy Comparisons [L/D = 12 (mono), L/D = 4 (segmented)]

![Energy Comparison Graphs]

Fig 5.19: Energy plots for different cases of S/D

5.8.5 Discussion:

![Penetration Depth Graphs]

Fig. 5.20 Penetration depth /collapsed length (P/L) vs. S/D for segmented penetrator of L/D ratio =4

From the stress and strain contour plots (Fig. 5.16–5.20), it is seen that there is a large magnitude of stress at the tip of the penetrator; this is basically due to impact on the target. Comparatively, the spacer material, which is weaker, has less magnitude of stress induced so it is easily strained. As the target is constitutionally weaker than the penetrator, it easily undergoes deformation with less magnitude of stress. Hence as we move away from the point of impact, the stress bands of decreasing magnitude can
be seen. Also it can be seen that even though the target is huge, a very small region around the point of impact is strained but the stress wave propagates throughout the material.

From the displacement plots it can be inferred that as the S/D ratio (= 1 to 2) increases, the depth of penetration decreases. Afterwards the depth of penetration slightly increases for S/D ratios (= 2 to 4). Again as the S/D ratio (= 4 to 6) increases, the depth of penetration decreases. For the remaining S/D ratio it again increases.

The initial kinetic energy goes on increasing with the increase in the size of the model governed by the equation KE= 1/2 mV^2. As the S/D increases, a greater amount of initial KE is possessed by the projectile and thus time for this energy to reduce to constant value also increases. For S/D = 1, KE = 195 e+9 kg-mm^2/s^2 and it takes approx 110 μs to fall to zero. This indicates that power transmitted is 1.77e+15 kg-mm^2/s^3 or 1.77 MW. Similarly for the other cases the rate of energy transfer was found to be 1.8, 1.77, 1.75, 1.6, 1.47 and 1.45 MW for S/D = 0, 1, 2, 4, 6 and 8, respectively.

5.9 Comparison of segmented (L/D=6) and monolithic (L/D=18) penetrator

5.9.1 von Mises Stress Comparison

Fig.5.21: von Mises Stress Contour plots for different cases of S/D
5.9.2 Equivalent Plastic Strain Comparisons \([L/D = 18 (Mono), L/D = 6 (Segmented)]\)

Fig. 5.22: Plastic Strain Contour plots for different cases of S/D

5.9.3 Displacement Comparisons \([L/D = 18 (Mono), L/D = 6 (Segmented)]\)

Fig. 5.23: Displacement plots for different cases of S/D
5.9.4 Energy Comparisons [L/D = 18 (Mono), L/D = 6 (Segmented)]

Fig. 5.24: Energy plots for different cases of S/D

5.9.5 Discussion

Fig. 5.25 Penetration depth /collapsed length (P/L) vs. S/D for segmented penetrator of L/D ratio = 6

From the stress and strain contour plots (Fig. 5.21–5.22), it is seen that there is a large magnitude of stress at the tip of the penetrator; this is basically due to impact on the target. Comparatively, the spacer material, which is weaker, has less magnitude of stress induced so it is easily strained. As the target is constitutionally weaker than the penetrator, it easily undergoes deformation with less magnitude of stress. Hence as we move away from the point of impact, the stress bands of decreasing magnitude can be seen. Also it can be seen that even though the target is
huge, a very small region around the point of impact is strained but the stress wave propagates throughout the material.

From the displacement plots it can be inferred that as the S/D ratio (\(= 1 \text{ to } 4\)) increases, the depth of penetration decreases to a value of 26 mm. Afterwards the depth of penetration increases for S/D ratios (\(= 6 \text{ to } 8\)). This can be explained as follows: as initially S/D is small, the L/D effect dominates; the segment material plays the major role. As S/D increases, there is a gradual decrease in strength of the penetrator, and a limit is reached at which the depth of penetration is minimum. After that limit the spacer materials aid in the improvement of depth of penetration.

The initial kinetic energy goes on increasing with the increase in the size of the model governed by equation \(KE = \frac{1}{2} mV^2\). As the S/D increases, a greater amount of initial KE is possessed by the projectile and thus time for this energy to reduce to constant value also increases. For S/D= 1, KE = 280 e+9 kg mm\(^2\)/s\(^2\) and it takes approx 150 \(\mu\)s to fall to zero. This indicates that power transmitted is 1.86e+15 kgmm\(^2\)/s\(^3\) or 1.86 MW. Similarly for the other cases the rate of energy transfer was found to be 1.92, 1.86, 1.875, 1.736, 1.613 and 1.52 MW for S/D = 0, 1, 2, 4, 6 and 8, respectively.

### 5.10 Comparison of segmented (L/D=8) and monolithic (L/D=24) penetrator

#### 5.10.1 von Mises Stress Comparison

Fig.5.26: von Mises stress Contour plots for different cases of S/D
5.10.2 Equivalent Plastic Strain [L/D = 24 (Mono), L/D = 8 (Segmented)]

Fig. 5.27: Plastic Strain Contour plots for different cases of S/D

5.10.3 Displacement Comparisons [L/D = 24 (Mono), L/D = 8 (Segmented)]

Fig. 5.28: Displacement plots for different cases of S/D
5.10.4 Energy Comparisons [L/D = 24(Mono), L/D = 8 (Segmented)]

**Fig. 5.29**: Energy plots for different cases of S/D

**Fig. 5.30** Penetration depth/collapsed length (P/L) vs. S/D for segmented penetrator of L/D ratio = 6

### 5.10.5 Discussion:

From the stress and strain contour plots (Fig. 5.26–5.30), it is seen that there is a large magnitude of stress at the tip of the penetrator; this is basically due to impact on the target. Comparatively, the spacer material, which is weaker, has less magnitude of stress induced so it is easily strained. As the target is constitutionally weaker than the penetrator, it easily undergoes deformation with less magnitude of
stress. Hence as we move away from the point of impact, the stress bands of decreasing magnitude can be seen. Also it can be seen that even though the target is huge, a very small region around the point of impact is strained but the stress wave propagates throughout the material.

It can be inferred that at lower values of S/D ratio (= 1 and 2), the depth of penetration is almost constant. Later, with the increase in S/D ratio there is a decrease in depth of penetration and reaches a minimum at S/D = 5. Afterwards, there is an increase in the penetration depth with increasing S/D ratio. This can be explained as follows: because of large value of L/D ratio (8), the effect of spacers is negligible at low values of S/D (= 1 and 2). However, as S/D increases, the spacer length becomes significant. The spacer material being weaker has a negative effect on the depth of penetration causing it to drop to a minimum (at S/D = 4). As the spacer length increases further, at comparable values of S/D and L/D, the spacer materials aid in the penetration.

The initial kinetic energy goes on increasing with the increase in the size of the model governed by the equation KE= \( \frac{1}{2} mV^2 \). As the S/D increases, a greater amount of initial KE is possessed by the projectile and thus time for this energy to reduce to constant value also increases. For S/D= 1 KE = 370 e+9 kg mm\(^2\)/s\(^2\) and it takes approx 190 \( \mu \)s to fall to zero. This indicates that power transmitted is 1.94e+15 kgmm\(^2\)/s\(^3\) or 1.94 MW. Similarly for the other cases the rate of energy transfer was found to be 2, 1.94, 1.809, 1.82, 1.69 and 1.56 MW for S/D = 0, 1, 2, 4, 6 and 8, respectively.

Fig.5.31 Penetration depth /collapsed length (P/L) vs. S/D for Monolithic penetrator
5.11 Plots for Monolithic Penetrators:

For monolithic penetrators, it can be inferred from the above plots that even though the depth of penetration, $P$, increases with the increase in $L/D$ ratio, the penetration efficiency, i.e. $P/L$, decrease.

5.12 Combined Plots of Segmented Penetrators:

5.12.1 Plots with parameter as $L/D$

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Fig. 5.32 Penetration depth / collapsed length ($P/L$) vs. $S/D$ for segmented penetrator of $L/D$ ratio
It can be seen that as the L/D ratio increases, the penetration efficiency (P/L) decreases even though the depth of penetration (P) increases. For a given L/D ratio the effects of variation of P/L and P with different S/D ratios are discussed in earlier sections. It is seen that for the L/D = 2 case, the P/L is the maximum for S/D = 1, which shows that this combination is the optimal one shown in Fig. 5.32.

5.12.2 Plots with parameter as S/D

Fig. 5.33: Combined plot of penetration depth / collapsed length (P/L) vs. L/D ratio for different S/D ratio
It can be seen that the trend followed is the same in the plot of P/L vs. L/D for different cases of S/D, with the exception being the case of S/D = 1, L/D = 2. This case is the point of maximum efficiency and hence can be the considered as the optimum. This conclusion is also evident from the plots in the previous section as shown in Fig. 5.33.