Growth of Hole in Thin Plates Under Hypervelocity Impact of Cylindrical Projectiles

M. Hosseini¹, H. Abbas²* and N.K. Gupta³

¹ Associate Professor, Department of Civil Engineering, Lorestan University, Khorramabad, P.O. Box 465, Iran, Email: mo_hosseini78@yahoo.com.
² Professor, Department of Civil Engineering, King Saud University, Saudi Arabia, on leave from Aligarh Muslim University, Aligarh 202 002, India.
³ Professor, Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi 110 016, India.

ABSTRACT

The study of characterization of the growth of hole in thin targets has been the subject of extensive study for the last five decades for its application in space industry. The representation of the diameter of hole in the shield or some other component of a spacecraft as a function of various projectile and target parameters helps in the assessment of its damage and hence its performance and functioning. The paper presents an exhaustive analysis of experimental data available in literature on the strike of cylindrical projectiles on thin metallic targets for the prediction of hole-diameter in the target. The discrepancies in the test data used in the analysis have been highlighted. A non-dimensional model for the prediction of hole-diameter is developed which incorporates the geometric and material properties of target as well as the projectile and the angle of strike of the projectile. The proposed model not only works well for different materials independently but also for all materials data of normal and oblique strike.

1. INTRODUCTION

The subject of hypervelocity has received a great deal of individual attention, particularly from late 1950s. A collection of available knowledge of cratering and penetration under Hypervelocity impact conditions was compiled in Ref. [1] and a review of the physical processes involved was presented in Ref. [2]. A summary report containing substantial bibliographies in each section on the study of hypervelocity impact phenomena categorizes the topic into empirical approaches, theoretical approaches, and engineering considerations [3]. Another useful bibliography dealing with the subject of meteoroid impact is contained in a companion report [4]. Similarly, hypervelocity impact is also substantially covered in a bibliography concerning aspects of the meteoroid hazard [5]. The special topic of the effects of hypervelocity jets and projectiles on rocks has received a separate review [6]. A collection of articles presenting a combination of surveys and research information is covered in Ref. [7].

The most common method of protecting a spacecraft from the impact of meteoroids and orbital debris is to place a Whipple shield, named after Fred Whipple [8], which is a thin metal plate outboard of a spacecraft’s wall. The study of characterization of the growth of hole in thin targets has been the subject of extensive study for the last five decades for its application in space industry. The representation of the diameter of hole in the shield or some other component of a spacecraft as a function of various projectile and target parameters helps in the assessment of its damage and hence its performance and functioning. The diameter of hole in thin targets may also give an idea about the characteristics of the projectile. When a meteoroid strikes the shield, it breaks the meteoroid thus reducing the impact on the body of the spacecraft.

Some analytical solution for predicting hole diameter under hypervelocity impact are available in literature [9-11] which are based on the principles of fluid mechanics but this model also involves empirical constants. The influence of body curvature of the target on the penetration hole size was included in Ref. [12] but its effect was found to be of the order of other uncertainties and was thus negligible. For the impact of spheres on plates, the morphology of lip structure was found to be dependant on the ratio of plate thickness to sphere
diameter especially when this ratio is large. Many empirical relations are available in literature [13, 14] but most of them are applicable for the data for which these have been developed. It is with the objective of developing a hole growth model in thin targets under the hypervelocity impact of projectile that the present study has been undertaken. The proposed model employs the properties of materials, geometry of both the projectile and the target, and may be used for variety of materials and velocity range.

The velocity range of interest to spacecraft industry is up to 18 km/s because the anticipated average impact velocity of orbital debris for spacecraft in low earth orbit is about 11 km/s and of micro-meteoroids is about 18 km/s. In the beginning, the velocity range in experimental studies was up to 1 km/s using powder guns which later in 1960’s increased to 3 km/s using light-gas gun. It was, however, only just the beginning to enter into the truly hypervelocity regime for most targets and projectile materials. Several researchers [15-19] carried out experimental investigations involving the impact of spherical and cylindrical projectiles on thin plates of the same or different material at impact velocity varying from 1 km/s to 15 km/s using the light-gas guns. The data used in the present analysis is mostly from Marshall Space Flight Center (MSFC) and Space Debris Impact Facility (SDIF) which mainly involves Aluminium projectile and Aluminium targets. The remaining data involving many other materials was obtained from other reports and papers [17, 18]. The use of data covering a large variety of materials and their combination greatly enhances the scope of the present study.

2. HOLE GROWTH PHENOMENON

When a projectile strikes a target plate, it forms crater and if sufficient kinetic energy is there, it perforates the target. On the basis of experimental observations and physics involved, some salient features of the phenomenon of hole growth in the target are as given below:

i) The perforation may cause formation of lips or it may be a clean hole with fine lips, if any, depending upon the values of impact velocity and characteristics of projectile and the target.

ii) If the target is perforated, diameter of hole is usually greater than the projectile diameter but it may be less because of any of the following reasons:
   • Elastic recovery of lips of hole of the target
   • Projectile gets damaged because of being weaker than the target material
   • Projectile gets burnt or vaporize on impact

Out of the 102 data used in this paper, only three data gives hole diameter less than the projectile diameter.

iii) Increase in the velocity of strike of projectile increases the diameter of hole because of increase in the inertia of lips of the hole.

iv) The lips of hole in thicker target plates have more inertia and therefore large hole-diameter.

v) For oblique of strike of projectile, the hole in the target plate has been found to be elliptical.

3. MODELS FOR HOLE-DIAMETER

Previous work by researchers in predicting hole diameters in thin plates due to hypervelocity impact has yielded several models. Schonberg et al. [20] used tests conducted at MSFC’s SDIF involving cylindrical projectiles. The diameters in the thin bumpers were all of elliptical shape due to a slight yaw of the projectile prior to impact with the major and minor diameters given by [20]:

\[
\frac{D_{h\text{maj}}}{D_p} = 8.323 \left( \frac{V}{c_f} \right)^{0.617} \left( \frac{T_t}{D_p} \right)^{1.639} e^{1.664\theta} + 1.40 \tag{1}
\]

\[
\frac{D_{h\text{min}}}{D_p} = 2.309 \left( \frac{V}{c_f} \right)^{0.302} \left( \frac{T_t}{D_p} \right)^{0.561} \cos^{-0.177} \theta + 1.0 \tag{2}
\]

where, \( D_p \) is the diameter of cylindrical projectile; \( D_h \) is the diameter of hole in target plate; \( T_t \) is target thickness; \( V \) is striking velocity of projectile; and \( \theta \) is the angle of strike of projectile.

As the angle of strike approaches to zero (i.e. normal strike), the hole approaches to circular, therefore, major and minor diameter should approach each other which is not happening in these models. Therefore, these equations cannot be used for low angle of strike especially when the strike is normal. The data used in the
paper does not contain the major and minor diameters for oblique strike – only the mean diameter is available, therefore, mean of the two values obtained by the above two equations will be used for assessing its performance. It is also observed that for some projectile impact data, predicted minor diameter given by Eq. (2) is greater than major diameter given by Eq. (1), therefore these models are valid only for the data for which these have been developed.

Hill [13] proposed a model based on the data taken from different sources including the data pertaining to oblique strike ($\vartheta = 0^\circ$ to $73.7^\circ$) but his model was independent of the angle of strike:

$$\frac{D_h}{D_p} = 2.627 \left( \frac{V}{c_p} \right)^{-0.016} \left( \frac{V}{c_t} \right)^{0.213} \left( \frac{\rho_p}{\rho_t} \right)^{0.147} \left( \frac{T_p}{T_t} \right)^{0.145} \left( \frac{T_t}{D_p} \right)^{0.285}$$

(3)

Where, $T_p$ is projectile thickness; $c_p$ and $c_t$ are speed of sound in projectile and target materials respectively; $\rho_p$ and $\rho_t$ are the densities of projectile and target materials respectively; $C_1, C_2, p1, p2, p3, p4, p5 & p6$ are the model parameters. Hill [13] proposed another model with additive constant:

$$\frac{D_h}{D_p} = 3.274 \left( \frac{V}{c_p} \right)^{-0.021} \left( \frac{V}{c_t} \right)^{0.165} \left( \frac{\rho_p}{\rho_t} \right)^{0.105} \left( \frac{T_p}{T_t} \right)^{0.105} \left( \frac{T_t}{D_p} \right)^{0.207} - 0.671$$

(4)

but the difference between the two models is very small.

4. EXPERIMENTAL DATA

The data used in the analysis is taken from Refs. [17-18, 20-21], which makes a total of 102 data points. The data consists of seven parameters viz. projectile diameter, thickness of projectile, target thickness, projectile velocity, angle of strike and material of target and projectile. The frequency distribution of these parameters and some non-dimensional parameters is plotted in Figs. 1 to 4. The range of these parameters for the data may be seen in these figures wherein the lower and upper limit is shown in the first and the last range of parameters plotted on X-axis of Figs. 2 to 4.

It is observed that the diameter of cylinders mainly varies from 0.559 to 8 mm making a total of about 88% data and most of the data is for 5 to 8 mm diameter (37%). The thickness of target plate varies from 0.04 to 4.75 mm and about 81% of the data is for plate thickness less than 2 mm. Only 17.7% of the data has target thickness greater than projectile diameter (Fig. 1) wherein the material of projectile as well as the target is Aluminium and about 67.6% of the data is for target thickness less than 50% of the projectile diameter (Fig. 3).

The velocity of strike of projectile varies from 1.11 to 12 km/s (Fig. 2) but very few data is available for velocity greater than 8 km/s (5.9%) as seen from Fig. 2. Most of the data is for velocity range of 3-8 km/s (70.6%) and the data for velocity greater than 3 km/s is 76%. The velocity of strike of projectile is mostly greater than the velocity of sound in target material (65.7%) but there are only 1% data points having velocity more than two times the velocity of sound in target material.

It is seen from Fig. 6 that the angle of strike of projectile varies from $0^\circ$ (i.e. normal strike) to $73.7^\circ$ but most of the data has angle of strike less than $5^\circ$ (77.5%). There are only 6.9% data points wherein the angle of strike is greater than $45^\circ$ (Fig. 3).

The projectile density varies from 0.36 to 5.36 times the target density (Fig. 4). In 66% of the data, the density of projectile and target is nearly same. There are three material combinations for projectile and target materials. About 66% of the data uses same material (Aluminium) for projectile as well as the target plate. Lighter material for projectile as compared to the target has been used in 7.2% data points and heavier material for projectile has been used in 26.8% of the data points.
The observations made from the above discussion are:

- Most of the data available in literature is for normal strike and very few data is available for oblique strike.
- The data of oblique strike is for $V \leq 8$ km/s and most of oblique strike is in the range of 4-7.25 km/s.
- Most of the normal strike data is also for $V \leq 8$ km/s and there are only five data points in which the velocity crosses this value.
The diameter of hole for oblique strike is mostly less than 2.7 times the projectile diameter with only two exceptions.

5. PROPOSED MODEL

A model proposed by Chant [12] for spherical projectiles, which has the analytical basis as it is based on the principle of fluid mechanics, has been used with some modification:

\[
\frac{D_h}{D_p} = C_1 \left( \frac{V}{c_p} \right)^{p1} \left( \frac{V}{c_t} \right)^{p2} \left( \frac{\rho_p}{\rho_t} \right)^{p3} \left( \frac{T_p}{T_t} \right)^{p4} \left( \frac{T_t}{D_p} \right)^{p5} \cos^p \theta + C_2
\]

(5)

This model is similar to Hill’s model [13] and embraces all the basic geometrical and material properties used to describe the behavior of shock waves in solid materials as well as the angle of strike.

It is observed from the experimental data that there are some experiments in which the type of material of target as well as the projectile is same. It is to be noted here that even though the material of target and the projectile is Aluminium but the density and velocity of sound in the materials is not the same because of the different type of Aluminium. The models have been developed for these groups independently for normal and oblique strike of projectile so as to observe the behaviour of different materials and to see whether a combined model may be given or not?

The model parameters derived for various groups of data along with the mean percentage of error are given in Table 1. There is three group of data for normal strike (Al-Al; Al-St; St-Al). For oblique strike, there is only one group of Al-Al material. The models have also been developed for normal as well as oblique strike based on all materials data.

The models have also been developed based on all the data including normal as well as oblique strike. In these models four variations are considered by including or ignoring the additive constant, $C_2$ and power, $p$.

Model – 1: $C_2 = 0$, $p = 0$; Model – 2: $C_2 \neq 0$, $p = 0$;
Model – 3: $C_2 = 0$, $p \neq 0$; Model – 4: $C_2 \neq 0$, $p \neq 0$.

### Table 1 Model parameters for different derived models

<table>
<thead>
<tr>
<th>Material</th>
<th>No. of Data</th>
<th>Model Parameters</th>
<th>Mean absolute Error$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$C_1$ $C_2$ $p1$ $p2$ $p3$ $p4$ $p5$ $P6$</td>
<td>Normal Strike, $\theta = 0$</td>
</tr>
<tr>
<td>Al-Al</td>
<td>51</td>
<td>2.125 0.398 -0.360 0.600 -0.215 0.260 0.267 0</td>
<td>19.4% (19.5%)</td>
</tr>
<tr>
<td>Al-St</td>
<td>07</td>
<td>2.200 0.455 -0.310 0.650 -0.235 0.268 0.367 0</td>
<td>9.0% (11.6%)</td>
</tr>
<tr>
<td>St-Al</td>
<td>21</td>
<td>3.284 -0.7 -0.018 0.165 0.105 0.105 0.207 0</td>
<td>7.6% (13.1%)</td>
</tr>
<tr>
<td>All</td>
<td>79</td>
<td>2.856 0.545 -0.001 0.267 0.182 0.493 0</td>
<td>15.3% (17.1%)</td>
</tr>
<tr>
<td>Al-Al</td>
<td>23</td>
<td>3.284 -0.551 -0.038 0.200 0 0.095 0.207 0.01</td>
<td>6.0% (8.3%)</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>2.459 0 -0.239 0.450 -0.125 0.190 0.200 0</td>
<td>15.4% (Model-1)</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>2.132 0.385 -0.310 0.561 -0.165 0.235 0.240 0</td>
<td>15.2% (Model-2)</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>2.45 0 -0.192 0.362 -0.100 0.165 0.190 -0.085</td>
<td>15.3% (Model-3)</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>2.185 0.445 -0.354 0.600 -0.175 0.220 0.265 -0.090 15.0% (Model-4)</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ first material code is for projectile and second for target; $^2$ Value within brackets is the error for Model – 4

The models developed for one-material for normal strike have mean error within 15.3% but the model based on all data of normal strike is having mean error of 17.1% which is not very much higher. Furthermore, the prediction of hole-diameter by Model – 4 for different material data sets is 0.1% to 2.6% higher than the models developed specifically for these data sets (Table 1). The models developed for the same material are obviously better for that data but these are also having lot of scatter and, therefore, one model for all of the data with only a little reduction in the value of mean absolute error is a better option.
The role of the velocity of strike in different models may be assessed by comparing the sum of parameters \( p_1 \) and \( p_2 \). It is observed from Table 1 that the sign of this sum is positive for models developed for one-material set as well as the model developed based on all the data, thus indicating that the hole-diameter increases with increase in the velocity of strike. The sign of parameter \( p_5 \) is also positive for these models.

The inclusion of additive constant \( C_2 \), and power \( p_6 \) have very little effect on the mean error. The decision of keeping or omitting model parameter \( p_6 \) should be based on the data of oblique strike. It is observed from Table 1 that the omission of parameter \( p_6 \) increases the mean error from 15.3% (Model – 3) to 15.4% (Model – 1) without additive constant and from 15.0% (Model – 4) to 15.2% (Model – 2) for models with additive constant for oblique strike data. Thus, the angle of strike has very little influence on diameter of hole. However, the parameter, \( p_6 \), may be retained because the inclusion of more oblique strike data in future may require it. It is also noted from here that the sign of parameter \( p_6 \) is negative because increase in the angle of strike reduces the damaging potential of the projectile.

The performance of Model-4 has been compared with Hill’s model [13] in Table 2. The performance of the proposed model is found to be better for all data combined and its performance is also good for Al-St and St-Al for normal as well as the oblique strike. Though the proposed model (Model – 4) is close to the Hill’s model but the inclusion of the angle of strike in the proposed model makes it better for normal strike.

<table>
<thead>
<tr>
<th>Material</th>
<th>No. of Data</th>
<th>Mean Percentage Error</th>
<th>Hill [13]</th>
<th>Model-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Strike, ( \theta = 0 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Al</td>
<td>51</td>
<td>27.9</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Al-St</td>
<td>07</td>
<td>12.1</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>St-Al</td>
<td>21</td>
<td>7.6</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>79</td>
<td>21.1</td>
<td>17.1</td>
<td></td>
</tr>
<tr>
<td>Oblique Strike, ( \theta &gt; 0 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Al</td>
<td>23</td>
<td>7.5</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>All Data Combined</td>
<td></td>
<td></td>
<td>18.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

The frequency of mean error for proposed model (Model -4) is depicted in Fig. 5 and the scatter in the prediction by the proposed model is shown in Fig. 6. It is observed from these figures that the mean error for 90% of the data is less than 15% and less than 3% data has error greater than 30%, which justifies the use of the model for the prediction of the hole-diameter.

6. CONCLUSIONS

An exhaustive analysis of the data available in literature for the prediction of hole-diameter in thin plates by cylindrical projectile is presented. The analysis highlights the discrepancies in the data so that the validity of models developed based on this data may be clear. The paper also justifies the use of single model for all of the materials.

The non-dimensional model proposed in the paper incorporates most of the geometric and material properties including the shock wave characteristics of the material and also the angle of strike. The model performs well for each material independently as well as for all the data.
Acknowledgement

Authors are grateful to Scott A. Hill for providing most of the data used in the present analysis.

References


