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BALLISTIC TESTS OF STS ARMOR PLATE,
USING 37-mm PROJECTILES

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BALLISTIC TESTS OF STS ARMOR PLATE,
USING 37-mm PROJECTILES

by
The Ballistic Research Group
Princeton University

Approved on March 2, 1943
for submission to the Division Chief

Approved on March 8, 1943
for submission to the Committee
The work described in this report is pertinent to the projects designated by the War Department Liaison Officer as CE-5 and CE-6, to the project designated by the Navy Department Liaison Officer as NO-11 and to Division 2 projects P2-101 and P2-402.

The work was initiated by H. P. Robertson. The main series of tests herein reported was performed by the group headed by L. A. Delsasso, the experiments being carried out by R. J. Emrich. The auxiliary tests at Palmer Physical Laboratory were performed by R. L. Kramer. The computations were carried out under the direction of, and this report was written by, R. J. Slutz, Technical Aide, Division 2. The experiments were performed under Contract OENMr-260 with Princeton University.

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BALLISTIC TESTS OF STS ARMOR PLATE,
USING 37-mm PROJECTILES

Abstract

Data are reported concerning the ballistic limit of STS armor -- Brinell hardness 270 -- for 37-mm projectiles (M51 without cap and windshield). Armor plates of thicknesses from \( \frac{1}{2} \) to 2 in. were used. Auxiliary tests with smaller caliber projectiles are also included; these tests were made on plates down to \( \frac{1}{3} \) in. thick.

1. Introduction

The ballistic limit of armor plate will be affected not only by the characteristics of the plate, but also by those of the incident projectile. Thus a given plate might be impervious to a highly frangible projectile, whereas it would be holed at the same velocity by another projectile having the same characteristics as the first except for being less brittle. It is customary in proof testing of armor to specify that the armor will fail for a given projectile at a given velocity. The shattering characteristics of the projectile may be one of the factors determining the performance.

In studying the physical bases of the behavior of armor plate it is desirable to separate the factors influencing this behavior in so far as it is practicable. Accordingly, one of the projects undertaken by the Ballistic Research Group at Princeton University is that of determining the ballistic limit of plate for nondeforming projectiles. A previous report\(^1\) presented the results of measurements

\(^1\)/ Ballistic Research Group, Princeton University, The ballistic properties of mild steel, NDRC Report A-111 (OSRD No. 1027).
made on mild steel at normal impact, using a wide range of projectile diameters and of thickness of plate. The present report is a record of an extension of that work to include measurements of the ballistic limit of STS plate for normal incidence by 37-mm projectiles. The study of the behavior of such plate at oblique incidence is at present delayed by a lack of 37-mm projectiles that will withstand such impact without shattering. Instead of waiting for the completion of the work at oblique incidence, we are reporting the data at present available for the information of those who are working on related problems. No attempt is made here to incorporate the data into a general physical theory of the behavior of armor; this report is a record of the carefully measured data needed for such a theory.

2. Plates

The armor tested consists of a series of STS plates obtained through the cooperation of the Naval Proving Ground at Dahlgren, Virginia. The plates are approximately 30 in. square and have thicknesses from $\frac{1}{2}$ to 2 in. They were especially selected to have very nearly the same hardmesses, as shown in Table I. The $\frac{1}{4}$-in. and 3/8-in. plates were taken from plates that had previously, at the Naval Proving Ground, passed acceptance tests against caliber .30 armor-piercing projectiles at 0° obliquity, and the remainder from plates that had passed acceptance tests against 6-in. or 8-in. projectiles at high obliquity.
Table I. Properties of plates tested. Tensile tests conducted at the Naval Proving Ground; Brinell hardness readings taken at Princeton.

<table>
<thead>
<tr>
<th>Plate Number</th>
<th>Nominal Thickness (in.)</th>
<th>Yield Point (lb/in.²)</th>
<th>Tensile Strength (lb/in.²)</th>
<th>Elongation (percent)</th>
<th>Reduction of Area (percent)</th>
<th>Brinell Hardness Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>1/4</td>
<td>133 100</td>
<td>143 100</td>
<td>19.0</td>
<td>50.8</td>
<td>294</td>
</tr>
<tr>
<td>D-2</td>
<td>3/8</td>
<td>122 300</td>
<td>144 000</td>
<td>18.5</td>
<td>54</td>
<td>283</td>
</tr>
<tr>
<td>D-3</td>
<td>5/8</td>
<td>110 800</td>
<td>125 500</td>
<td>22</td>
<td>67</td>
<td>264</td>
</tr>
<tr>
<td>D-4</td>
<td>1</td>
<td>106 900</td>
<td>127 200</td>
<td>21</td>
<td>61</td>
<td>272</td>
</tr>
<tr>
<td>D-5</td>
<td>1 1/2</td>
<td>107 300</td>
<td>129 300</td>
<td>22</td>
<td>62</td>
<td>257</td>
</tr>
<tr>
<td>D-6</td>
<td>1 1/2</td>
<td>106 300</td>
<td>125 800</td>
<td>22</td>
<td>63</td>
<td>271</td>
</tr>
<tr>
<td>D-7</td>
<td>2</td>
<td>107 500</td>
<td>130 500</td>
<td>22</td>
<td>65</td>
<td>289</td>
</tr>
</tbody>
</table>

3. Experimental conditions

The main series of tests was made with standard 37-mm M51 projectiles from which the cap, windshield and tracer had been removed for the reasons discussed in detail in the report on mild steel.2/ Certain auxiliary tests were also made, using caliber .244 smoothbore projectiles, Type 1, and caliber .50 E6 projectiles. These projectiles are also discussed in detail in the report on mild steel.

The 37-mm and caliber .50 tests were made at the NDRC range.3/ The plates were hung with cables attached to the top corners; hence they can be considered as freely suspended. The residual velocity of the projectile was measured by a light-screen chronograph having a 1-ft base line.4/ The striking velocity was measured both with a

2/ Reference 1.
spiral chronograph using 1-ft base-line light screens close to the plate and with an Aberdeen chronograph utilizing foil screens on a 50-ft base. The velocity measured by the Aberdeen chronograph was corrected for the loss of velocity between the screens and the target plate. This corrected value was then averaged with the value obtained from the light-screen chronograph to give the striking velocity of the projectile. The caliber .244 tests were made on the double ballistic pendulum in Palmer Physical Laboratory, using clamped 6 × 6-in. pieces cut from the larger plates.

In accordance with the method described in reference 1 on mild steel, the observed data were used to compute striking energy, residual energy, limit energy, Thompson F-coefficients, and so forth. In computing the striking and residual energies of a projectile it is customary to use the weight of the projectile as recovered after firing. This practice amounts to neglecting the energy of any soft parts of the projectile — such as bands — that shear off on impact. In this series of experiments, however, the projectiles shattered with sufficient frequency to make it necessary to use a different method in some cases. For the projectiles that shattered, then, the weight to be used in calculating the kinetic energies was determined by taking the projectile weight before firing and correcting according to the average loss of weight observed in the projectiles that did not shatter.

Fig. 1. Thompson F-coefficient versus e/d, where e is plate thickness and d is projectile diameter. O, caliber .244 smoothbore cores, X, caliber .50 E6 and 37-mm AP M51. Numbers by the symbols indicate the Brinell hardness of the plate. Small symbols indicate less reliable data. Data taken from the same plate are connected by dashed lines. Data for the main series of tests are indicated by X.
4. Results

The results obtained are presented in Table II, and plotted in Fig. 1, which gives the results of the main series of tests and also the auxiliary results obtained. This figure is plotted to the same scale as was used in reference 1, thus facilitating comparison. The Brinell hardness number of each plate is indicated beside the point giving the ballistic limit.

The quantities listed in Table II are discussed in reference 1.

Brief definitions of the symbols follow:

- \( e \) Average plate thickness.
- \( w \) Average projectile weight as recovered after firing.
- \( d \) Projectile diameter.
- \( E \) Limit energy, that is, the energy for which the residual energy is zero.
- \( P \) Average pressure between projectile and plate.
- \( v_\gamma \) Limit velocity, associated with limit energy.
- \( F \) Thompson F-coefficient; \( F = \sqrt{w/e} \cdot v_\gamma / d \).
- \( a \) Parameter related to \( P \) by
  \[ a = P \frac{2^{3/2} w'}{w} \left( \frac{w}{w'} - 1 \right)^{-1} \]
- \( w' \) Weight of a cylinder of diameter \( d \) and height \( e \) cut out of the target plate of thickness \( e \).
- \( s \) Slope of the graph of residual versus striking energy.
- \( \gamma \) Dimensionless parameter related to \( s \) by the equation,
  \[ s = e^{-\gamma w'/w} \]

5. Discussion

Attempts to obtain satisfactory data for the ballistic limit of 37-mm projectiles on the two thinnest plates proved fruitless.

For the \( \frac{3}{4} \)-in. plate, projectiles having high velocity were observed to lose approximately the amount of kinetic energy that would
Table II. **Ballistic data for STS plates.**

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>B_H (kg/mm²)</th>
<th>e (in.)</th>
<th>w (gm)</th>
<th>a/d</th>
<th>E₀ (ft lb/10²15/in²)</th>
<th>V₀ (ft/sec)</th>
<th>F (10³ units)</th>
<th>a (kg/mm²)</th>
<th>s</th>
<th>z</th>
<th>No. of Shots</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>294</td>
<td>0.255</td>
<td>5.252</td>
<td>1.04</td>
<td>399</td>
<td>402</td>
<td>1.490⁶</td>
<td>54.1</td>
<td>279</td>
<td>0.972</td>
<td>0.10</td>
<td>4</td>
</tr>
<tr>
<td>D-2</td>
<td>283</td>
<td>0.373</td>
<td>5.258</td>
<td>1.53</td>
<td>650</td>
<td>447</td>
<td>1.900</td>
<td>57.0</td>
<td>305</td>
<td>0.944</td>
<td>0.14</td>
<td>4</td>
</tr>
</tbody>
</table>

Caliber .244 smoothbore cores, d, 0.244 in.  (Type 1 of reference 1)

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>B_H (kg/mm²)</th>
<th>e (in.)</th>
<th>w (gm)</th>
<th>a/d</th>
<th>E₀ (ft lb/10²15/in²)</th>
<th>V₀ (ft/sec)</th>
<th>F (10³ units)</th>
<th>a (kg/mm²)</th>
<th>s</th>
<th>z</th>
<th>No. of Shots</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>294</td>
<td>0.254</td>
<td>29.45</td>
<td>0.512</td>
<td>1680</td>
<td>412</td>
<td>1.289</td>
<td>54.8</td>
<td>-</td>
<td>1.020</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>D-2</td>
<td>283</td>
<td>0.372</td>
<td>29.85</td>
<td>0.751</td>
<td>2504</td>
<td>420</td>
<td>1.565</td>
<td>55.3</td>
<td>294</td>
<td>0.992</td>
<td>0.03</td>
<td>4</td>
</tr>
<tr>
<td>D-3</td>
<td>264</td>
<td>0.596</td>
<td>29.02</td>
<td>1.20</td>
<td>3696</td>
<td>387</td>
<td>1.928</td>
<td>53.0</td>
<td>265</td>
<td>0.949</td>
<td>0.10</td>
<td>4</td>
</tr>
<tr>
<td>D-4</td>
<td>272</td>
<td>0.978</td>
<td>29.02</td>
<td>1.976</td>
<td>6965</td>
<td>447</td>
<td>2.647</td>
<td>56.9</td>
<td>-</td>
<td>1.009</td>
<td>-</td>
<td>4</td>
</tr>
</tbody>
</table>

Caliber .50 E6, d, 0.495 in.  (Type 20 of reference 1)

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>B_H (kg/mm²)</th>
<th>e (in.)</th>
<th>w (gm)</th>
<th>a/d</th>
<th>E₀ (ft lb/10²15/in²)</th>
<th>V₀ (ft/sec)</th>
<th>F (10³ units)</th>
<th>a (kg/mm²)</th>
<th>s</th>
<th>z</th>
<th>No. of Shots</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-3</td>
<td>264</td>
<td>0.596</td>
<td>754.2</td>
<td>0.411</td>
<td>25500</td>
<td>312</td>
<td>994</td>
<td>47.7</td>
<td>-</td>
<td>1.009</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>D-4</td>
<td>272</td>
<td>0.976</td>
<td>755.6</td>
<td>0.674</td>
<td>13720</td>
<td>326</td>
<td>1300</td>
<td>43.8</td>
<td>-</td>
<td>1.023</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>D-5</td>
<td>257</td>
<td>1.223</td>
<td>756.4</td>
<td>0.844</td>
<td>55600</td>
<td>332</td>
<td>1465</td>
<td>49.1</td>
<td>229</td>
<td>0.968</td>
<td>0.09</td>
<td>5</td>
</tr>
<tr>
<td>D-6</td>
<td>271</td>
<td>1.435</td>
<td>759.8</td>
<td>0.991</td>
<td>66900</td>
<td>340</td>
<td>1603</td>
<td>49.7</td>
<td>235</td>
<td>0.966</td>
<td>0.09</td>
<td>5</td>
</tr>
<tr>
<td>D-7</td>
<td>283</td>
<td>1.932</td>
<td>728.9⁶</td>
<td>1.334</td>
<td>95700</td>
<td>361</td>
<td>1957</td>
<td>51.2</td>
<td>247</td>
<td>0.948</td>
<td>0.10</td>
<td>2</td>
</tr>
</tbody>
</table>

Caliber .37-mm, d, 1.448 in.  (Type 23 of reference 1)

- a The number of shots used in reduction of data.
- bG, good; F, fair; P, poor.
- cBullets slightly blunted.
- dValue s = 1, assumed.
- eProjectile weight taken without band.
caliber .244 data, but also because of the scale effect, which would indicate that even for the same value of e/d the smaller caliber projectiles would have larger F-coefficients. We have no satisfactory explanation of this result, but more recent work indicates that the hardness of these plates is in the vicinity of the "hardness limit," above which is observed a decided drop in the ballistic limit of a plate. If the hardness at which this effect occurs were different for the different calibers, this might possibly serve as an explanation of the apparent discrepancy. More considerations along this line must wait for further experimentation. In any case, it will be seen that the remainder of the data are in definite agreement with the observations reported in reference 1, both in the dependence of the F-coefficient on the ratio e/d and in its dependence on the scale of the experiment.

The main series of tests -- using 37-mm projectiles -- is plotted in Fig. 1, the points being indicated by stars. It will be seen that these tests gave the customary slight increase of F with increase in the ratio e/d. The bullets were found to shatter with increasing frequency as the thickness of the plate was increased, until on the thickest plate -- 2-in. -- only 2 out of 10 shots gave acceptable measurements of both the striking and residual velocities. The F-coefficient for this plate is indicated by a small star in order to indicate that its value is somewhat less reliable than the values for the thinner plates.

Data taken with caliber .50 projectiles on the 5/8-in. and 1-in. plates are also shown in Fig. 1. For these projectiles on the
Tests were conducted on the ballistic limits of STS armor plate of 270 Brinell hardness and varying from 1/2 to 2 in. in thickness for 37 mm projectiles (M51 without cap and wind-shield). The tests with 37 mm ammunition gave the customary slight increase in the Thompson F-coefficient with increase in the ratio of average plate thickness over projectile diameter. The bullets were found to shatter with increasing frequency as the thickness of the plate was increased. Detailed data obtained from tests are given in graphs and tables. Auxiliary tests with smaller caliber projectiles were also made on plates down to 1/4 in. thick.
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