PENETRATION EQUATION FROM STEEL, ALUMINUM, AND TITANIUM PLATES BY DEFORMING PROJECTILES AT OBLIQUITY

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ABSTRACT

A similitude equation is offered for the penetration of steel, aluminum, and titanium plates at obliquities up to 70° by non-deforming steel projectiles. The proposed equation is confidenced and compared to the accuracy achieved in single projectile-single material relationships.

BACKGROUND

The penetration of armor by projectiles has become one of the classic applications of dimensional similitude techniques. One of the earlier, if not the earliest such application was made by L.T.E. Thompson, PhD, in 1927 at the Naval Proving Ground (NSWC predecessor), reference (a). During the 1930's and 40's, very extensive experimental work was conducted by A. V. Hershey, PhD, within similitude framework, references (b), (c), (d), and (e). Although the similitude analysis has included provision for considering materials of vastly different mechanical properties and indeed for different materials from the earliest derivation, no examples of such applications have been found by this writer. A similar comment can be found in reference (f) of 1973 vintage. The general data presentation for armor penetration seems to be a plot of V_{50} vs plate thickness for a given penetrator fired against a given plate material, reference (g). Such data presentations lead to very large armor handbooks of quite limited utility.

OBJECTIVE

The objective of the work reported in this paper is to determine whether the classical similitude analysis could be applied to the general case of ductile target material, non-deforming projectile-medium velocity penetration phenomena.

DATA SOURCES

Since this effort was purely an exercise in data analysis, existing data sources were used. These sources are listed in Table I. Reference (h) contains the results of the most extensive armor material data analysis known to this writer, penetration of Class B armor at obliquity angles of up to 70°. References (i) and (j) extended the data set to HY80 and HY100 steels. Reference (k) was used for mild steel. Reference (q) contains data on aluminum and titanium alloys. References (k) and (q) data should be used with caution since these alloys were in the process of development during the period in which the data was acquired.

APPROACH

The non-dimensional variables for the non-deforming projectile-ductile plate problem are shown in Table II. These variables were tested using Analysis of Variation (ANOVA) Techniques to determine which variables were significant. For those cases in which a single dependent variable was significant, third degree regression equations were generated and confidenced. For those cases in which multiple variables were significant, multiple linear regression techniques were used.

RESULTS

The results of the ANOVA are shown in Table III. Considering that three different materials (steel, aluminum, and titanium) were involved, it is somewhat surprising that only three variable groups appear significant. Table IV contains the regression equations. Note that the single material equations and the multiple mechanical property equations have similar R^2 values and standard deviations. The multiple material equation also appears to be reasonably accurate.

CONCLUSIONS

The similitude analysis provides a powerful tool which is applicable to the general case on ductile armor penetration by non-deforming projectiles in the medium velocity range.

A single equation may be used to predict penetration resistance of steel, aluminum, and titanium armors. Within a single material, the effects on penetration of mechanical property variation can be accounted for in the equation.

REFERENCES

(a) L. Thompson and E. B. Scott, Memorial de l'Artilleries Francaise, Vol. 6, pg. 1253, 1927.

(b) A. V. Hershey, The Plate Penetration Coefficient and Formulas for Penetration, 1st Seminar Report, Naval Proving Ground, Dahlgren, VA, 8 Jan 1942.

(c) A. V. Hershey, Analytical Summary Pt IV: The Theory of Armor Penetration, Naval Proving Ground Report #9-46, 1946.

(d) A. V Hershey, Ballistic Summary Part I: The Dependence of Limit Velocity on Plate Thickness and Obliquity at Low Obliquity, Naval Proving Ground Report #2-46.

(e) A. V. Hershey, Ballistic Summary Part IV: The Dependence of Limit Velocity on Plate Thickness and Obliquity at High Obliquity, Naval Proving Ground Report #1125.

(f) W. E. Baker, P. S. Westine, and F. T. Dodge, Similarity Methods in Engineering Dynamics: Theory and Practice of Scale Modeling, Hayden Book Company, Inc., 1973, pg 183.

(g) R. E. Cole, Armor and Ballistic Data Handbook, Naval Weapons Laboratory, Dahlgren, VA, TR.

(h) A. V. Hershey, Construction of Plate Penetration Charts or Tables, Naval Proving Ground Report #1120.

(i) W. H. Hall, Ballistic and Metallurgical Tests of HY80 Plate, Naval Proving Ground Report #1639.

(j) Naval Weapons Laboratory, Dahlgren, VA, Letter Report, TEGM:HWP:av, Ballistic Tests of HY100 - Steel Plate, 22 Sept 1959.

(k) Weapons Data, Fire, Impact, Explosion, OSRD Report #6053, 1945.

TABLE I

Target Material	Projectile Material	Striking Velocity Range (ft/sec)	Obliquity Range (°)	Ref
Class B, Steel Armor	Steel	500 - 3500	0 - 70	h
HY80 Steel	Steel	500 - 3500	0 - 70	i
HY100 Steel	Steel	500 - 3000	0 - 70	j
Mild Steel	Steel	500 - 3000	0 - 45	k
5083, 7039, Ti Aluminum	Steel	500 - 3000	0 - 45	q

TABLE II

NONDIMENSIONAL VARIABLES

where:

- m = Mass of the Projectile
- V_L = Limit Velocity
- σ = Yield Stress of the Target Plate
- α = Ultimate Stress of the Target Plate
- d = Projectile Diameter
- e = Target Plate Thickness
- θ = Obliquity Angle
- β, ψ = Angle Components of Projectile Yaw
- E = Young's Modulus of Target Plate Material
- μ = Poisson's Ratio of Target Plate Material
- ϵ = Strain to Failure of Target Plate Material
- γ = Change in Stress to Failure/Change in Strain Rate = $\partial\sigma/\partial\dot{\epsilon}$
- ρ = Density of Target Material

TABLE III

ANOVA RESULTS, EQUATION[1]

Source	DF	Sum of Squares	Mean Square	F Value
Total	222	706.91	-	-
Regression Variable #	4	692.37	173.09	2543.50
$\frac{m V_i^2 \cos^2\theta}{\sigma \epsilon d^3}$	1	686.71	686.71	10289.28
$\frac{m V_i^2 \cos^2\theta}{\alpha \epsilon d^3}$	1	1.72	1.72	25.73
$\frac{\sigma}{\alpha}$	1	.26	.26	3.84
$\frac{m}{\rho d^3}$	1	3.68	3.68	55.17
Residual	218	14.54	.06674	-

TABLE IV

REGRESSION EQUATIONS

Target Material	DF	Equation	Std D	R^2
All	223	$\frac{e}{d} = .01634\,(-7 + 1.4\,X - Y + 11.65\,Z)$	.258	.979
Class B, HY 80, HY 100, Mild Steel	147	$\frac{e}{d} = -1.54 + 20.18\,(X) + 12.95\,(X^2)^2 - 2.24\,(X^3)^3$	1.05	.993
Titanium	34	$\frac{e}{d} = -4.08 + 118.32\,Y\,214.6 - Y^2 + 193.4\,Y^3$	6.15	.989
Aluminum 5083	51	$\frac{e}{d} = -1.48 + 142.91\,Y - 28.66\,Y^2 + 2.69\,Y^3$	25.28	.81
Aluminum 7039	30	$\frac{e}{d} = .917 + 75.82\,Y - 4.48\,Y^2 + .883\,Y^3$	29.64	.92
All Aluminums	89	$\frac{e}{d} = -3.02 + 151.40\,Y - 35.24\,Y^2 + 3.79\,Y^3$	29.15	.85

where: $X = \frac{m V_L^2 \cos^2\theta}{\sigma \epsilon d^3}$ $\quad Y = \frac{m V_L^2 \cos^2\theta}{\alpha \epsilon d^3}$ $\quad Z = \frac{m}{\rho d^3}$

DF = Degree of Freedom