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PENETRATION EFFICIENCY OF TUNGSTEN PENETRATORS INTO GLASS FIBER REINFORCED RESIN/STEEL COMPOSITES AS A FUNCTION OF ASPECT RATIO AND IMPACT VELOCITY

S. Lampert, R. Jeanquartier and B. Lehmann

Defence Procurement Agency, Feuerwerkerstrasse 39, 3602 Thun, Switzerland

In the present study an extended version of an earlier published simple formula to estimate the total depth of penetration of tungsten long rod penetrators into layered composite targets is presented. In order to verify this formula different Glass Fiber reinforced Resin (GFR)/Steel composites were exemplary impacted by two different tungsten laboratory penetrators at variable velocity. The total depth of penetration into the different GFR/Steel composites was determined experimentally and afterwards compared with the calculated one. There is a good agreement between the calculated and the experimental depth of penetration.

INTRODUCTION

In an earlier study Jeanquartier and Lampert [1] presented a simple formula (1) in order to estimate the depth of penetration DOP of tungsten penetrators into layered composite targets. The composite target contains n layers of various materials. The layer thickness t_i and the semi-infinite penetration depth T_i of the corresponding layer at a certain impact velocity are known. At knowledge of the reference penetration depth P_{ref} at the same impact velocity into the backmost layer the total penetration depth P_{tot} can be calculated. In the study by Jeanquartier and Lampert [1] formula (1) was verified by comparison of the experiments and the calculations. The experiments were carried out with three penetrators showing almost equal aspect ratios but various lengths and the impact velocity was kept constant.

$$P_{tot} = \sum_{i=1}^{n} t_i + P_{ref} \cdot \left(1 - \sum_{i=1}^{n} \frac{t_i}{T_i} \right) \qquad (1)$$

The values of T_i and P_{ref} must be first determined by numerous semi-infinite penetration tests before applying formula (1). Furthermore, at present no functional relationship exists to characterize such an experimental data set. In order to apply formula (1) for example in a vulnerability assessment code it would be helpful if T_i and P_{ref} could be calculated by semi-empirical functions.

THREE-PARAMETER ANALYTIC FUNCTION

The parameter Pref that refers mostly to RHA as reference material can be determined with good approximation by the Odermatt formula [2,3] that is especially adapted to the impact of tungsten long rods into RHA. The parameter T can be estimated for example by a two-parameter exponential function (2) as suggested by Gooch et al. [4]. The parameters A and B must be adapted to a DOP data set containing corresponding impact velocities. However, this two-parameter function only applies to a single penetrator. Our aim was to find an adequate function that can be used for arbitrary penetrators at variable impact velocity. As base we used the two-parameter exponential function (2) with the parameters A and B. The parameter A was replaced by the product of two different terms (2a). The first term (2b) describes the influence of the aspect ratio according to the first term of the Odermatt formula presented in the study by Lanz and Odermatt [3] and the second term is due to the square root-rho-law for hydro-dynamic penetration.

$$T/L = A * \exp\left(-\left(\frac{B}{v}\right)^2\right) \tag{2}$$

$$A = f(\lambda) * \sqrt{\frac{\rho_P}{\rho_T}} \tag{2a}$$

$$f(\lambda) = \left[1 + a_1 * \frac{1}{\lambda} * \left(1 - \tanh\left(\frac{\lambda - 10}{a_2}\right)\right)\right] \tag{2b}$$

With
- T: Semi-infinite penetration (mm)
- L: Length of penetrator (mm)
- λ: Length to diameter ratio (-)
- v: Impact velocity (m/s)
- ρ_T: Density of target material (kg/m^3)
- ρ_P: Density of penetrator material (kg/m^3)

EXPERIMENTAL SET-UP

The firing experiments were conducted using sub caliber tungsten laboratory penetrators with aspect ratios λ=12.3, 13.4, 15.4 and 21.7 launched by sabots. The penetrators with λ=13.4 and 15.4 were fired from a laboratory gun with caliber 23 mm smoothbore barrel. The penetrators with λ=12.3 and 21.7 were fired from a laboratory gun with caliber 38 mm smoothbore barrel. The impact velocity was controlled using different weights of propellant. The distance from muzzle to target was approximately 15 m and two laser light barriers positioned in front of the target measured the projectile velocity. Yaw angles of the penetrators were detected stretching parallel sheets of paper directly in front of the target. Ballistic results from penetrators with striking Yaw angle in excess of 2° were disregarded.

Testing the applicability of function (2) with complementary functions (2a) and (2b) we conducted more than 30 semi-infinite penetration tests with the four laboratory penetrators against the material glass fiber reinforced resin (GFR) at variable impact velocity in the range of 1000–1600m/s and without obliquity. The investigated material GFR, a so-called ballistic Vetresit®, consists of 72% glass and 28% Epoxy resin. Simulating a semi-infinite target three to four 102 mm thick GFR blocks one behind the other were stretched in a steel frame.

In order to verify formula (1) using function (2) with the corresponding Fit-parameters a_1, a_2 and B composite targets consisting of GFR and rolled homogeneous armor (RHA) steel layers were impacted by two laboratory penetrators at variable impact velocity and with 0° obliquity. Figure 1 shows an schematically sketch of the experimental set-up.

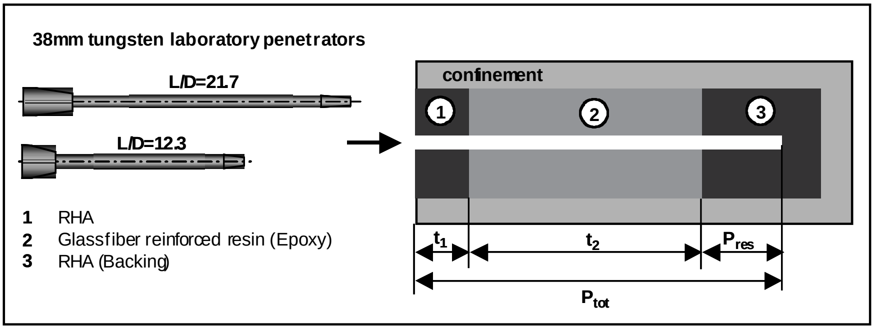

Figure 1. Experimental set-up.

RESULTS

In order to estimate the three parameters using the original lengths of the four penetrators with truncated conical nose shape the Levenberg-Marquard algorithm was applied. Possible effects of nose shape are not taken into consideration. The three parameters a_1, a_2 and B listed in Table1 however were adapted with good accuracy to the DOP data set of GFR. The complete DOP data set of material GFR is listed in Table 2. Figure 2 illustrates the normalized depth of penetration T/L into material GFR versus impact velocity for each of the four utilized laboratory penetrators. There is a good agreement between the experimental and the calculated data. Figure 3 shows the influence of aspect ratio in the defined range of λ>10. In the range of λ>25 the factor of aspect ratio influence becomes a value of 1 and therefore the penetration is independent of aspect ratio.

Verifying the extended version of formula (1) experimental and calculated total depth of penetration data into GFR/RHA composites were compared. In formula (1) the variables P_{ref} and T were calculated by function (2) using the corresponding parameters a_1, a_2 and B listed in Table 1. For RHA the parameters a_1 and a_2 were determined and examined by Lanz and Odermatt [2] and parameter B was calculated with the functional relationship (5) developed by Jeanquartier and Odermatt [5].

$$B = \sqrt{\frac{c * R_m}{\rho_P}} \tag{5}$$

With $c = 22.1 + 1.27 * 10^{-2} * R_m - 9.47 * 10^{-6} * R_m^{\ 2}$
R_m : Tensile strength of the target material steel (MPa)
ρ_P : Density of penetrator material (kg/m3)

With R_m=1260 MPa for RHA the output of function (5) is B=1.28km/s (1280m/s). The results of the experimental and the calculated total DOP data are listed in Table 3.

Table 1. Parameters of three-parameter fit

Target Material	Density [g/cm ^{3}]	Tensile Strength [MPa]	Fit Parameters applied in functions (2)		
			a_1	a_2	B [m/s]
Glass fiber reinforced resin (Epoxy) GFR	1.9	250 – 320	**3.8**	**9.7**	**1144**
Armor steel RHA	7.85	1255 – 1270	3.94	11.2	1280

Table 2. Semi-infinite DOP data set of glass fiber reinforced resin (epoxy)

Laboratory Tungsten Penetrator L/D ratio	Length L [mm]	Diameter D [mm]	Mass [g]	Velocity [m/s]	Depth of Penetration into GFR T [mm]	T/L
12.3	110.6	9	115.3	1030	123	1.11
12.3	110.6	9	115.3	1215	173	1.57
12.3	110.6	9	115.3	1221	176	1.59
12.3	110.6	9	115.3	1293	191	1.73
12.3	110.6	9	115.3	1427	223	2.02
12.3	110.6	9	115.3	1509	236	2.13
12.3	110.6	9	115.3	1618	254	2.30
13.4	53.7	4	11.3	1278	85	1.58
13.4	53.7	4	11.3	1368	95	1.77
13.4	53.7	4	11.3	1470	104	1.94
13.4	53.7	4	11.3	1490	107	1.99
13.4	53.7	4	11.3	1574	115	2.14
13.4	53.7	4	11.3	1652	119	2.22
15.4	58.6	3.8	11.3	1323	93	1.59
15.4	58.6	3.8	11.3	1375	97	1.66
15.4	58.6	3.8	11.3	1438	105	1.79
15.4	58.6	3.8	11.3	1470	108	1.84
15.4	58.6	3.8	11.3	1477	108	1.84
15.4	58.6	3.8	11.3	1529	119	2.03
15.4	58.6	3.8	11.3	1534	120	2.05
15.4	58.6	3.8	11.3	1535	126	2.15
15.4	58.6	3.8	11.3	1540	123	2.10
15.4	58.6	3.8	11.3	1543	117	2.00
15.4	58.6	3.8	11.3	1545	115	1.96
15.4	58.6	3.8	11.3	1558	115	1.96
15.4	58.6	3.8	11.3	1568	115	1.96
15.4	58.6	3.8	11.3	1583	118	2.01
15.4	58.6	3.8	11.3	1637	115	1.96
21.7	173.5	8	151	1299	250	1.44
21.7	173.5	8	151	1565	333	1.92

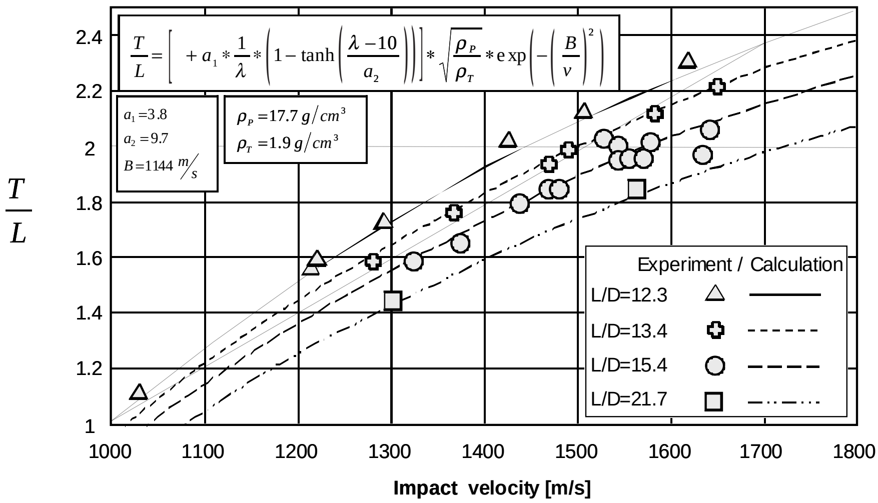

Figure 2. Three-parameter fit for laboratory tungsten penetrators.

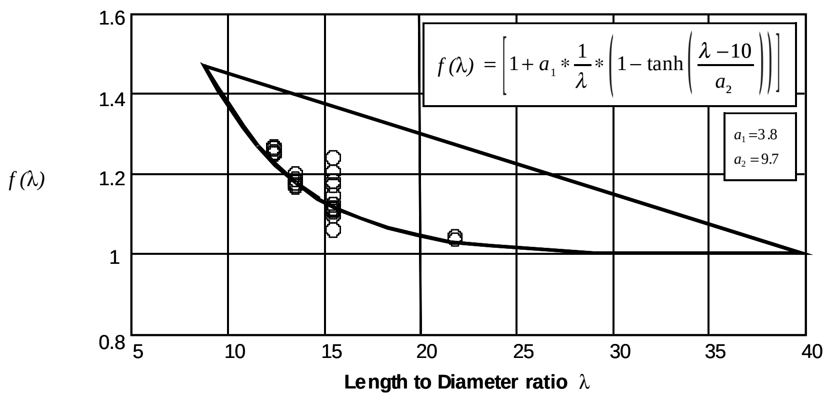

Figure 3. Length to diameter ratio λ as a factor of influence f (λ).

Home
Table of Contents

Table 3. Comparison between the experimental and calculated total DOP

Laboratory Tungsten Penetrator		GFR/RHA Composite (According to Figure 1)			Velocity [m/s]	Total Depth of Penetration		Relative Deviation
L/D ratio	L [mm]	t_1 [mm]	t_2 [mm]	P_{res} [mm]		Experiment P_{ex} [mm]	Calculation P_{calc} [mm]	$(P_{ex} - P_{calc})/P_{ex}$
21.7	173.5	0	102	60.8	1300	**162.8**	**163**	-0.1 %
21.7	173.5	0	102	92	1565	**194**	**196.5**	-1.3 %
21.7	173.5	21.1	102	52.8	1460	**175.9**	**184.2**	-4.7 %
21.7	173.5	21.1	102	27	1260	**150.1**	**157.3**	-4.8 %
21.7	173.5	21.1	102	74.9	1600	**198**	**200**	-1 %
21.7	173.5	21.1	202.8	44.5	1620	**268.4**	**259**	+3.5 %
12.3	110.6	0	102	26.5	1220	**128.5**	**130.5**	-1.6 %
12.3	110.6	0	102	43.2	1420	**145.2**	**151.3**	-4.2 %
12.3	110.6	0	102	46.7	1500	**148.7**	**158.7**	-6.7 %
12.3	110.6	0	102	57.5	1610	**159.5**	**168**	-5.3 %

CONCLUSION

We can conclude, that at the example of the material GFR, the Tree-Parameter analytic function (2) is applicable not even for metallic but also for non-metallic materials with relatively good approximation.

Verifying formula (1) extended by function (2) various GFR/RHA composite targets were impacted by two laboratory penetrators with L/D=12.3 and 21.7 without obliquity. The relative deviation between the experimental and the calculated total depth of penetration yields less than +7% at all trials.

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