Penetration into Ductile and Brittle Materials Research at the Institute for Industrial Mathematics, Beer-Sheva, Israel

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Extensive research has been recently conducted at the Institute for Industrial Mathematics, Beer-Sheva, Israel concerning engineering problems of high-speed impact and penetration into protective structures. The presentation is a selection of these investigations. The protective armors under discussion are manufactured of ductile (metal), brittle (ceramics, concrete, etc.) and composite materials. A general, problem-oriented approach is applied to the analysis and examination of this field, within a wide-range research program ordered by Israeli Defense Industries. In the framework of the program, advanced straightforward models are developed resulting in empirical, analytical and computer solutions, intended for firsthand use in the practical work of armor designers.

The following penetration problems are discussed:

1. *Initial penetration. Projectiles vs metal armor of arbitrary thickness: an analytical model.* An impulse model is developed of purely hydrodynamic formulation. It enables the projectile velocity loss to be determined at the first, nonstationary stage of the penetration. In the case of very thin armor plate, the model provides for the residual velocity estimation with good accuracy for a wide range of ultimate strength limits of material.

2. *Penetration. Short projectiles (bullets, fragments) vs metal slabs: dimensional analysis.* Penetration of a metal projectile into a metal slab has been extensively studied both experimentally and theoretically, and numerous empirical correlations were obtained based on experimental data for the final crater's geometry depending on the projectile's velocity, strength and inertial properties of materials. Treatment of experimental data and numerical calculations in the framework of diverse theoretical models require, in particular, the knowledge of the so-called effective dy-

namic hardness of the materials. Unlike static hardness, dynamic hardness is not a well-defined material constant. This raises significant difficulties in data processing resulting in non-uniform description of penetration parameters and the choice of available empirical correlations in practice. In the present study, effective dynamic hardness is obtained on the basis of similarity analysis. The main dimensionless parameters for numerous projectile-target pairs are revealed by data processing at a wide range of impact velocities. The "master" curves are built for parameters of the crater providing values of effective dynamic hardness of the slab material.

3. *Penetration. Long projectiles vs metal slabs: an analytical model.* A new dynamic thermoplastic flow model of high-speed penetration has been created, based on the conservation laws with regard to plastic flow resistance. An advancement is representation of constrained flow of projectile and target materials. In contrast to the well-known Tate model used at present, the model allows the sizes of the crater and the mushrooming head of the eroded projectile to be determined. This analytical model is simple in use and gives required accuracy in determining penetration parameters. Determination of the mushrooming radius of the projectile is of essential practical importance, most notably for composite armor. The model is based on account taken of (a) the localization of the thermoplastic shear, initiation and propagation of the melting wave in the target material resulting in separation of plastic jets, and (b) the resistance to the plastic flow under the forward-to-back transformation of the jets of the projectile and target materials. Good agreement is achieved with experimental data.

4. *Perforation. Long projectiles vs a metal plate of moderate thickness: an analytical model.* A two-stage perforation model is developed. The first stage is described by the above model (see 3), while the other is based on a so-called "spherical plastic flow" model presentation. Two parameters introduced into the second model are to be determined by the suggested experiments. The model enables the residual parameters of the projectile to be estimated.

5. *Perforation. Short projectiles vs a thin metal plate: an empirical model.* A simple formula based on energy considerations is introduced for perforation of thin metal plates by a small projectile. This formula allows the ballistic limit and residual velocities to be determined. The formula is well confirmed by independent experiments with perforation by bullets of thin armor plates of various hardnesses and thicknesses. The formula is used in composite armor optimization.

6. *Penetration/perforation. Brittle armor: an analytical model.* Foundation of the model for penetration accompanied by radial crack zone dynamics has been

elaborated. This model allows the cracking area of a brittle target to be determined as well as the resistance to penetration. It also permits the optimization of ceramic armor tiles. This model is based on account taken of (a) crack propagation and arrest, (b) the crack closure phenomenon, and (c) wave radiation.

7. *Penetration/perforation. Composite multi-layered armor: a computer model.* A new model has been created of multi-layered fabric armor as part of a composite armor. Simulation of penetration-perforation based on this model allows the mechanical parameters of the composite armor to be optimized. The model is based on account taken of (a) the projectile shaping during primary metal armor perforation, (b) the processes of target delamination and fracture, (c) dynamic interaction of layers, and (d) wave radiation.

8. *Penetration/perforation. Short projectiles vs light metal-fabric armor: software.* In order to examine the stopping power of such armor, a computer model of penetration is developed. An unsteady-state formulation is applied to elasto-plastic dynamics of a multi-ply composition for successive perforation of plies in the package. The designed computer program unites various mechanical models into a user-friendly, fast CPU-time PC-oriented tool. Results of computer simulation are presented and their practical applications are discussed.