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NUMERICAL SIMULATION OF THE PERFORMANCE OF TANDEM WARHEADS

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Tandem warhead systems consist of a precursor shaped charge and a following kinetic energy (KE) projectile containing a high explosive filling. They are designed to penetrate hardened structures especially targets with concrete layers. This paper presents numerical simulations to analyze the penetration process of tandem systems. This includes detailed material models especially the description of concrete behavior under highly dynamic loads. Simulation models for the penetration of shaped charge jets and KE projectiles in concrete are presented and the combined performance in the tandem system is analyzed. Experimental date are used to verify the simulation results.

INTRODUCTION

The numerical simulation of a tandem warhead (see fig.1) requires the description of the penetration process of the shaped charge jet and the KE projectile as well as their interaction. The most important phenomena are:

- Shaped charge jet formation (velocity gradient)
- Shaped charge stretching during penetration process
- Erosion of jet and target during penetration
- Crater formation including damage of concrete target
- KE projectile penetration (nearly rigid body penetration)

The shaped charge jet is explicitly modeled with a conical shape (see fig.1) and the corresponding velocity gradient between jet tip and jet tail. The data for this explicit jet description (jet radius as a function of jet velocity) can come either from experiment or from simulations with empirical codes for shaped charge analysis. The simulation model thus includes grids for the shaped charge jet, the penetrator case and the concrete target. In this paper we use a Lagrange description for all these grids. This is the procedure that is the most convenient one to model the above mentioned physical processes.

An important point in the analysis is an exact simulation of the crater profile created by the shaped charge jet and the reduction of the strength of the penetrated concrete target. The available material model for concrete has the capability for this type of analysis. Additionally the model includes the dynamic interaction of the following KE projectile

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with the crater walls of the target. The presented procedure thus allows the assessment of the performance of tandem warhead systems. The important steps for this simulation (material model for concrete, shaped charge penetration, KE projectile penetration, complete sequence of tandem system) are presented in the following sections.

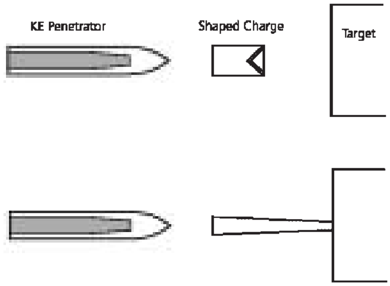

Fig. 1 – Tandem warhead and explicit modeling of shaped charge jet.

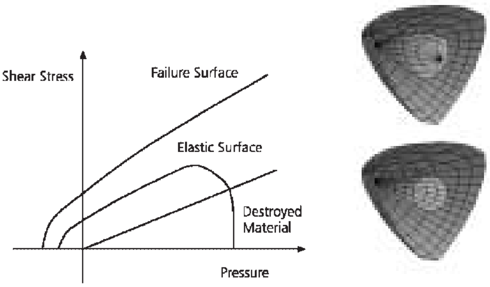

Fig. 2 – Schematic representation of limit surfaces of concrete.

MATERIAL DESCRIPTION

The simulation contains the three materials: concrete target, high strength steel penetrator case and aluminum jet. The two metals steel and aluminum are described with a Johnson Cook model for the deviatoric strength behavior. Very important is the material description of the concrete target, especially the weakening of the target due to the passage of the shaped charge jet. For this purpose the RHT model, developed at EMI is used [1].

Concrete has the following experimental material properties:

- Tensile strength is 1/10 of compressive strength
- Shear strength is pressure dependent
- Accumulation of damage (failure surface depends on damage)
- Porosity and existence of micro cracks between mortar and aggregates

The description of these phenomena requires a complex model for the characterization of concrete. The EMI RHT model includes the static as well as the dynamic range and thus can be used for penetration processes of shaped charge jets and KE penetrators. The following gives a short summary of the main properties of the model:

- Porous equation of state
- Limit surfaces pressure dependent (elastic, failure and residual strength)
- Limit surfaces depend on all 3 invariants of stress tensor
- Strain rate effects
- Damage characterization (essential features are taken from [2])

Fig. 2 shows the schematic location of the different limit surfaces in the stress space especially the change of the failure surface due to damage development. The damage model is of special importance because it describes the weakening of the concrete target due the penetration of the shaped charge jet. Damage occurs as soon as the failure surface in the stress space is reached during a loading process. In the uniaxial compression test damage occurs in the stress strain diagram in the region following the maximum compression stress. The material behavior is then characterized by macroscopic crack development. The following phenomena have to be described:

- Reduction of the failure surface with increasing damage (material with a complete damage can not sustain any tensile stresses any more)
- Reduction of elastic constants

Damage accumulation is described by a damage variable D that depends on the permanent plastic and volumetric strains. The parameter D is in the range 0 to 1, where the parameter 0 corresponds to undamaged material and the value of 1 corresponds to maximum damage. The numerical simulation gives the damage variable within the concrete target and thus allows the calculation of the strength reduction caused by the penetration of the shaped charge jet into the concrete.

CRATER FORMATION BY SHAPED CHARGE JET

The precursor shaped charge is modeled explicitly. The actual shape depends on the stand off between shaped charge and target. This is due to the velocity gradient within the jet that causes continuous stretching of the jet until break up into individual particles. The physical properties of the jet at the time of impact on the target are:

- Conical shape (small radius at jet tip and continuously increasing to the jet tail)
- Aluminum jet
- Jet diameter at tip 5.4 mm
- Jet diameter at end 10.4 mm
- Jet length 180 mm
- Velocity gradient (6900 m/sec at tip, 2000 m/sec at tail)

The shaped charge jet is modeled with a high resolution mesh. It is divided in 70 parts with equal velocity which corresponds to a resolution of the velocity gradient in intervals of 100 m/sec.

The shaped charge jet stretching is a dynamic process with high strain rates and leads after a certain time to the break up of the jet into individual particles. From experiment it is known that the strains occurring during jet stretching are in the range of 1200%. This must be taken into account in the simulations, too. The simulation code uses an erosion algorithm that deletes elements from the calculation as soon as a predefined value of the effective plastic strains is exceeded. This value is set to 12 which corresponds to the above mentioned experimental results. Together with the high resolution grid this allows the simulation of highly dynamic penetration processes.

Fig. 3 shows the conical shaped charge jet at time of impact and the corresponding crater profile after complete erosion of the jet 0.4 msec later. A significant region of the target shows reduced strength due to the passage of the jet (damage parameter shows values near 1, which means that the material cannot longer sustain tensile stresses). The penetration depth is 610 mm and is in very good agreement with the results from empirical codes used for shaped charge design.

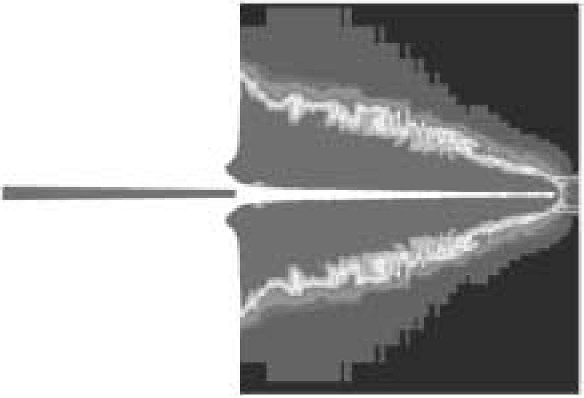

Fig. 3 – Explicitly modeled shaped charge jet and created profile.

An additional check of the penetration depth can be done with the help of analytical formulae describing the penetration of stretching jets in the purely hydrodynamic limit. The penetration depth P of a continuously stretching jet follows (see e.g.[3]):

$$P = Z_0 \cdot \left[\left(\frac{v_s}{v_e} \right)^{1/\gamma} - 1 \right]$$

$$\gamma = \sqrt{\frac{\rho_t}{\rho_j}}$$

with the notation:

Z_0	virtual origin of jet
v_s	jet tip velocity
v_e	jet tail velocity
ρ_t	target density
ρ_j	jet density

Using the parameters of the above defined shaped charge jet the analytical penetration depth is 680 mm. The numerical value is with 610 mm lower which can be explained by the fact that the numerical model shows not a continuous velocity gradient (but intervals of 100 m/sec) and mainly that the simulation includes strength effects which reduce the achieved penetration. Therefore it can be concluded that the numerical simulation gives reasonable results for the penetration depth compared with empirical codes as well as analytical models. This gives the confidence that the whole crater profile (radius versus depth) is reasonably reproduced.

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KE PROJECTILE PENETRATION

In this section results from experiments and simulations on the penetration of KE projectiles into undamaged concrete are presented (without precursor charge). The following penetrator design was used:

Caliber	60 mm
Length	508 mm
Mass	6039 g

The target consisted of two concrete blocks of diameter 96 cm, length 1 m and a steel casing. The concrete compressive strength was 35 N/mm^2. The experimental results were (see [4] and [5] for experimental details and interpretation of penetration depth within cavity expansion theory):

Impact velocity	509 m/sec
Penetration depth	114.5 cm

Fig. 4 shows the front and rear side of the target after impact of the KE projectile.

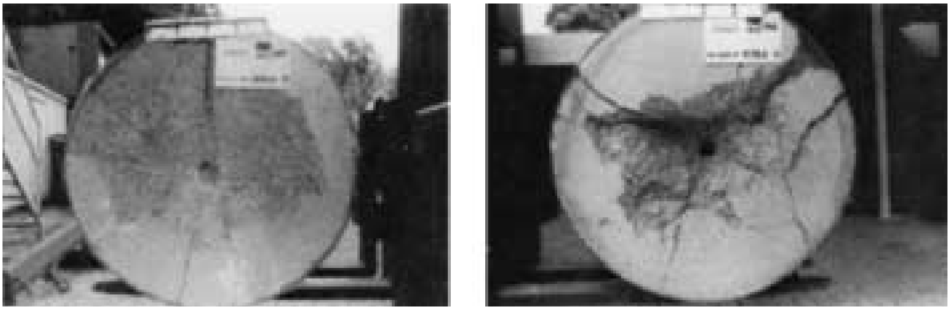

Fig. 4 – Front and rear side of concrete target after impact.

The corresponding results from the simulation are shown in fig. 5 with the configuration at the time of impact and after the penetrator came to rest. The calculated penetration depth is 119 cm and agrees very well the experimental value of 114.5 cm.

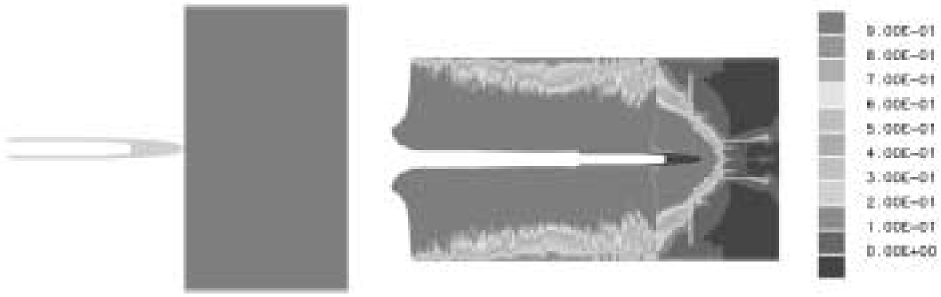

Fig. 5 – KE penetrator at impact and at end of penetration.

TANDEM SYSTEM PERFORMANCE

The assessment of the tandem system efficiency combines the effects of the shaped charge and the KE penetrator. The numerical simulation includes the penetration process of the KE projectile into the damaged concrete target from fig. 3. The weakening of the target is due to the formed crater (reduction of volume) and the reduced strength in the neighborhood of the jet crater (damage description in the material model). The target thickness for the simulation was 140 cm. Fig. 6 shows the configuration at time of impact and 5.5 msec later. At this time the penetrator exits the rear of the target. The damage of the target is so severe that the penetrator perforates the target with a residual velocity of 225 m/sec. Compared to the KE penetrator performance of 114.5 cm in an undamaged target the penetration depth in the tandem system is significantly increased.

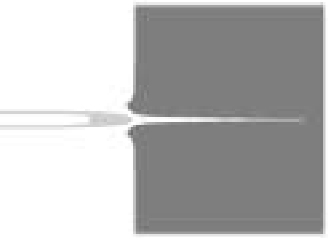

Fig. 6a – KE projectile impact target on damaged concrete target.

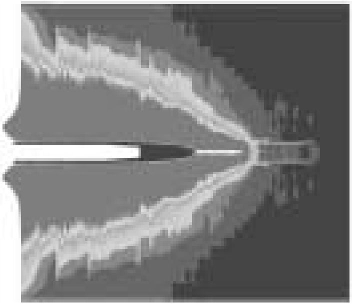

Fig. 6b – KE proectile penetration in damaged concrete target.

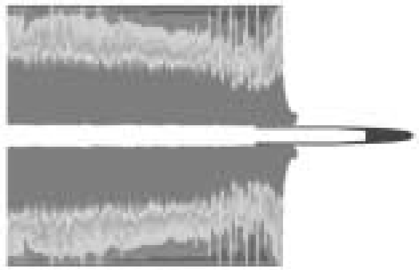

Fig. 6c – KE projectile exits target.

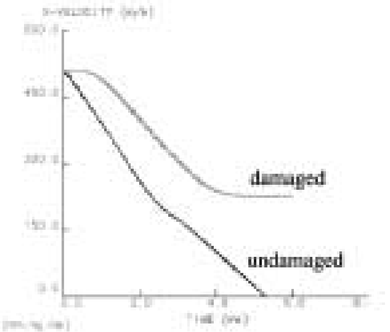

Fig. 7 – Velocity of KE projectile for damaged and undamaged target.

Fig. 7 compares the velocity decay of the KE projectile in the undamaged and damaged concrete targets. The acceleration in the damaged target is lower (the slope of the velocity curve is smaller) and the projectile has a residual velocity of 225m/sec after perforation of the concrete block.

The simulations demonstrate the principal feasibility of a complete numerical simulation of the tandem system performance.

SUMMARY

A numerical model for the complete assessment of the tandem warhead performance against concrete targets has been presented. An important point to analyse were the combined effects of the shaped charge and the KE penetrator. Attention has been addressed to the material modeling of the concrete target especially to a description of the material damage due to the penetration of the precursor shaped charge to reproduce crater profiles. The penetration depth produced by shaped charge jets and KE penetrators were verified with experimental results and analytical, empirical calculations. The performance of the KE penetrator including a precursor shaped charge is significantly increased.

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