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Numerical and experimental ricochet investigation of a spin-stabilised projectile

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Micro Abstract
Numerical simulations in LS-DYNA are used for a qualitative investigation, as measurement precision limits the determination of projectile nutation under oblique impact. The parabolic flight trajectory causes nutation in spin-stabilised projectiles. They rotate at an angle contained between the inertial axis and the relative velocity vector. Especially at the critical angle, where the projectile no longer penetrates but ricochets, influential parameters need to be determined.

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Introduction

Expanding urbanisation in developing countries poses new challenges. History has demonstrated that conflict and large-scale disasters are likely to occur where large populations reside [3]. Future peace-keeping missions are in closed urban locations, where foot soldiers find themselves surrounded by house walls and close to their armoured vehicles. The likelihood of projectile ricochet arises in a closed environment in event of combat. For each target and projectile configuration, there exists a critical obliquity angle θ_c, which means that the projectile ricochets only at an angle higher than θ_c. Influential parameters supporting ricochet, such as target thickness [4], and projectile velocity [9], have been studied in the past. This study focuses on target complexity, where an armour steel plate was formed in one axis, at a diameter D (Figure 1 b). The investigation was extended, involving the influence projectile yaw angle caused by nutation (Figure 1 c, d). Numerical simulations are used for a qualitative investigation, and supply a tendency of yaw angle influence on the projectile behaviour, at oblique impact of a rounded surface.

1 Spin-stabilised Projectiles

In order to keep projectiles stable during their flight, grooves inside the gun barrel give them an initial spin around their length or rotational axis. The spinning mass creates gyroscopic forces that keep the projectile length axis resistant to the destabilising overturning torque [7]. The projectile is in a sort of imbalance most of this time, as these forces readjust each other and the nose actually describes a small arc in the air, known as nutation (Greek for nodding) [6]. This nutation, contained between the projectile axis and the relative velocity vector, is stated here in the plane of incidence as yaw angle α_t. Previously conducted work has estimated that the nutation shifts the projectile nose at an angle up to $\alpha_t = 4°$ from its COG (centre of gravity) [12] (Figure 1 c, d)

2 Experiments

Oblique impact experiments were conducted launching $7.62 \times 51\ mm$ projectiles at $8\ mm$ thick armour steel targets of $350\ HB$ hardness. The first challenging part was to determine the angle of obliquity θ. Figure 1 b) shows the definition of θ which was experimentally deterimined by varying the impact height y.

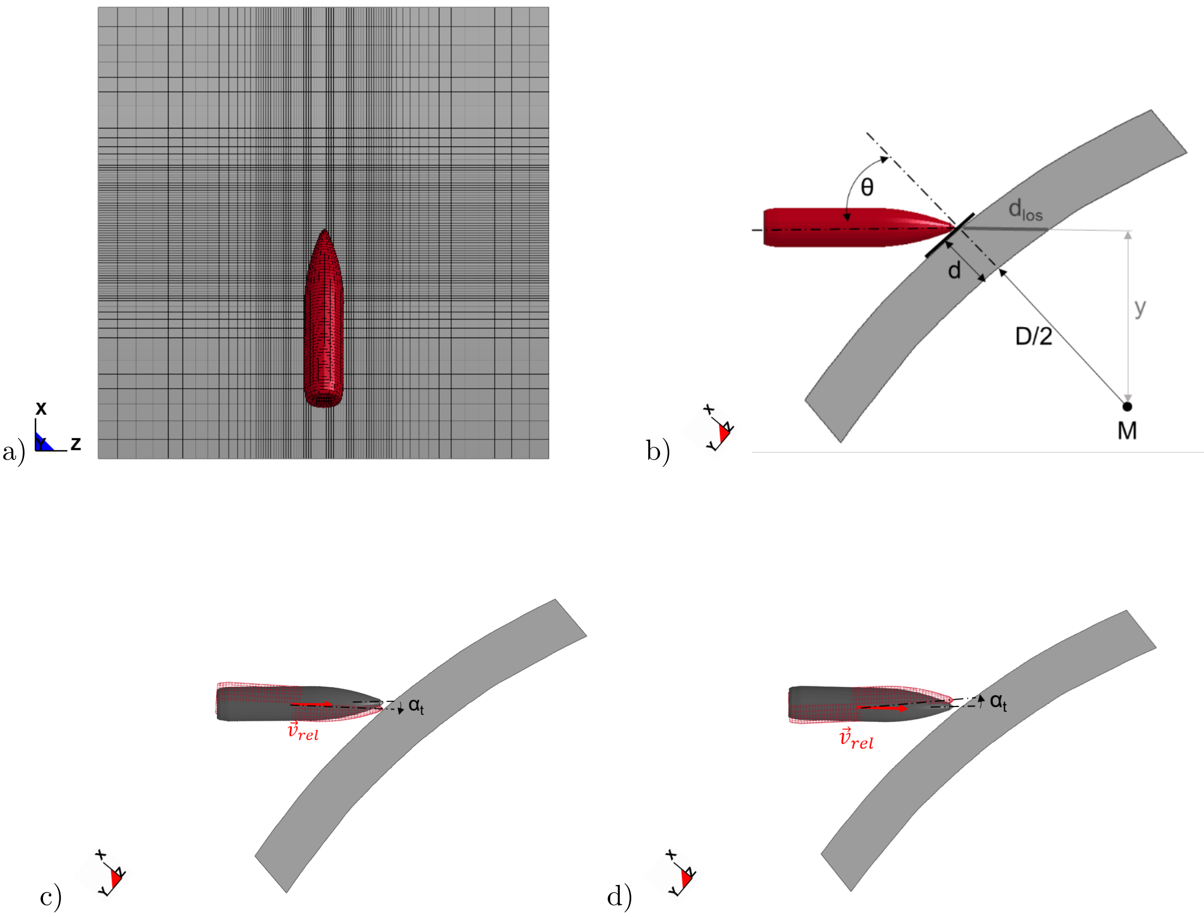

Figure 1. Mesh a) and projectile position b) for oblique impact on rounded surface; yaw case A with upper most position c) and case C with lower most position d) shown for $\theta = 50°$.

3 Numerical model

The numerical model is designed as a full three-dimensional model (Figure 1 a) for future ricochet investigations on more complex target surfaces. The numerical model was set up using solid, fully integrated brick elements in an explicit Lagrangian solver. The mesh was created for a plate impact [11] and transferred to the rounded application. Modelled were the projectile core and the rounded plate.

3.1 Material model

For both parts, the Johnson-Cook (JC) material model [5] was applied and the Von-Mises stress flow σ_y is given in the following equation:

$$\sigma_y = [A + B\bar{\varepsilon}_p^n][1 + c \cdot \ln(\dot{\varepsilon}^\star)][1 - T_m^\star] \quad (1)$$

Where a further detailed description and parameters for the target material is found in literature [1, 2]. Constitutive parameters for armour steel and projectile core have been determined from tensile tests [1, 11]. Additional required material parameters for the projectile core material were also taken from literature [1].

3.2 Equation of state

The JC material model needs an additional equation of state (EOS) to define the material properties, defined by the Gruneisen EOS:

$$p = \frac{\rho_0 c^2 \left[1 + (1 - \frac{\gamma}{2})\mu - (\frac{\alpha}{2}\mu^2)\right]}{\left[1 - (S_1 - 1)\mu - \frac{S_2\mu^2}{(\mu-1)} - \frac{S_3\mu^3}{(\mu-1)^2}\right]} + (\gamma + \alpha\mu)E_0 \tag{2}$$

Where E_0 is the internal energy per unit volume, intercept c and slope coefficients S_1, S_2, S_3, Gruneisen coefficient γ, and volume correction α. Literature provides the EOS parameters for core [4] and for the target [8]

3.3 Failure criteria

The target was defined with the JC fracture model shown below:

$$\varepsilon_f = [D_1 + D_2 e^{D_3\sigma^*}][1 + D_4 ln(\dot{\varepsilon}^*)][1 + T^*] \tag{3}$$

Where is the equivalent plastic fracture strain, is the stress triaxiality factor, and D_1, D_2, D_3, D_4, and D_5 are fracture model constants [5]. Solid elements are defined to fail with $\sigma_1 \geq \sigma_{max}$, with σ_1 is the maximum principal stress and σ_{max} is the principal stress at failure.

4 Comparison plane and shaped plate impact

The current limited precision on the experimental determination of θ also impedes a valuation on θ_c. The influence on the rounded surface on ricochet occurrence, and the critical oblique angle θ_c were numerically realised. Solitary, displaced nodes from plate impact to the rounded target shape, influence the results on core ricochet [10]. The rotational momentum of the core, due to its spin-stabilisation, was neglected, and a possible nutation influence was calculated instead by defining two possible extreme positions. The nutation was represented numerically by rotating the core nose around the COG with $\alpha_t = 4°$ counter-clockwise from its initial position around z-axis; defining the upper most position as case A (Figure 1 c). The position C is defined by the clockwise core rotation around the z-direction, representing the lower-most position (Figure 1 d). The initial position, without yaw, is stated as O, where case A and C are compared to. When the projectile core hits under α_t in case A or C, the closer impact angle θ gets to θ_c the more influential the yaw angle becomes. It agrees with the already observed results on oblique plate impact [11], where the influence on core yaw for penetration and ricochet cases is described in detail [10, 11].

Conclusions

This study gives an understanding of the dependency of the rounded plate surface on the critical ricochet angle under oblique impact. The set-up was a hard core projectile, impacting rounded armour steel plates under different impact angles. The remaining core velocity after penetration and ricochet, as well as the critical angle from where the first ricochet occurred, were of interest. Previously validated numerical simulations from plane plate impact where used for the rounded surface. While facing limitations in experimental measurement precision, the results could be used to validate the numerical changes from plate impact to a rounded surface. By comparing numerically, the resultant core displacement, it was observed that the rounded surface favours ricochet. The simulation was extended for investigating the influence of the yaw angle on the ricochet scenario. It is numerically shown, that the closer the impact occurred to the critical

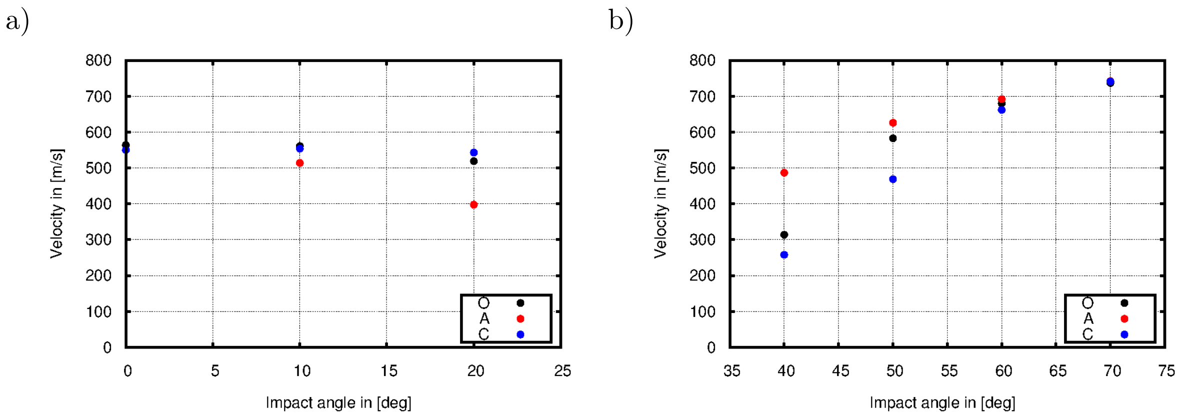

Figure 2. Yaw angle influence on projectile after penetration a) and ricochet b) from a rounded surface

angle, the larger was the influence of the yaw angle. The results provide ground work for further numerical investigations into the influence of different, experimentally hard to determine, parameters, and their influence on projectile behaviour and energy after oblique impact.

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