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Numerical simulations of normal and oblique impact on single and double-layered aluminium Al6061-T6 plates

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SUMMARY

Studies of ballistic penetration into metal plates and their numerical simulation currently present an important topic in ballistics, however, no congruent results have been presented so far, especially when it comes to impacts on multi-layered plates. Presently, as far as ballistic limits are concerned, the choice between layered and monolithic structures is not completely straightforward and unproblematic. The effect of introducing air gaps between metallic layers is not fully understood and explained either. Furthermore, these issues are more investigated for normal impacts than for oblique impacts for which only limited results are available. Therefore, the aim of this paper is to conduct a numerical analysis in order to evaluate the effect on the ballistic limit on layered targets for both normal and oblique impacts. A validated numerical methodology will be used, though validated with a limited number of experiments. The target material is an Al6061-T6 aluminium alloy the mechanical behaviour of which (hardening, strain rate, failure, etc.) is already known and described. Several configurations will be numerically tested and the results critically evaluated.

Key words: *normal impact, oblique impact, numerical simulation, double-layered, air gap, LS-DYNA.*

1. INTRODUCTION

One of the main problems one has to face during the analysis of a bullet penetration regards the physical mechanism of failure that is strictly related to the shape of a projectile. Different types of bullets exhibit different penetration mechanisms, which consequently brings about diverse damage shapes. For instance, ogival bullets penetrate a target by a ductile hole growth mechanism, whereas blunt projectiles manifest a plug shear penetration mechanism [1]. In the case in which multilayer targets are considered, the bullet penetration becomes much more complicated. In Ref. [2] the authors have shown that using a double-layer configuration and blunt projectiles, the failure mechanism of the first plate is shear plugging whereas the second plate fails due to a ductile hole growth. If ogival projectiles are used, both plates fail due to a ductile hole growth mechanism. This scenario indicates already how difficult it is, owing to a high number of parameters involved, to model a penetration numerically and in a unique and comprehensive manner. A more interesting aspect of penetration regards the effect of having a layered target, compared to the monolithic solution. Many studies focus on the evaluation of the change of the ballistic limit using a monolithic plate or a multi-layer structure, but these studies mainly discuss normal impacts. Therefore, the motivation for present study is to investigate the effect of obliquity on the penetration into single and multi-layer targets. A high number of contrasting results that can be found in literature illustrate the complexity of the problem of penetration, especially that of double-layer solutions. In Ref. [3] authors have shown that the ballistic limit of a thin aluminium plate increases more rapidly by increasing the monolithic thickness rather than by adding new layers. They have also demonstrated that, using the same global thickness for a monolithic plate or a multi-layer structure, the monolithic configuration has higher ballistic limit. Different results have been obtained in Ref. [4] using blunt and ogival bullets on a WELDOX700E steel plate. The authors have shown that by changing the monolithic thickness (from *6* to *12 mm*) and by using blunt projectiles, the ballistic limit increases by *20%*. However, if the global thickness of *12 mm* is maintained, but two steel layers (*6+6 mm*) are used, the ballistic limit increases by *50%*. The addition of an air gap between the two layers causes an intermediate increase of *40%*. The same authors also tested ogival bullets obtaining results very different from the previous ones. When using ogival bullets, the doubling of the monolithic thickness results in an increase of the ballistic limit by *60%*. However, if the double-layer configuration is used, the ballistic limit decreases by *10%*. The addition of an air gap between the layers results in a decrement in the ballistic limit (*-10%*). In Ref. [5], authors have carried out a normal direction impact test using *7.62* APM2 and *7.62* NATO ball bullets on five different types of steel showing that the ballistic limit is not affected by the use of either a monolithic or a double-layer configuration. However, if an air gap is created between the two layers, the ballistic limit decreases. Already this brief literature review makes clear that the problem of penetration is multifaceted and requires many additional studies. Starting out with these considerations, an investigation of obliquity effect on penetration with single, double and double with air gap configuration appears very interesting indeed. Therefore, this paper focuses on the numerical simulation of the mentioned penetration problems seeking out a better solution to increase safety using a metallic shield subjected to oblique, ogival bullet impacts. It is important to state that, as the first step, the numerical model will be validated against the literature data (normal and *30°* obliquity impact on a single layer plate). Once this is done, the same validated model will be extended to simulate a more complex load scenario (i.e. the effect of an oblique impact on multi-layer targets) that will be likewise considered in the present paper.

2. NUMERICAL ANALYSIS

2.1 Numerical model

Numerical analyses carried out in this paper were performed in LS-DYNA commercial finite element code. To decrease computational time, the problem was considered symmetric, therefore only half of the model has been modelled.

In order to describe the constitutive law, a modified version of Johnson-Cook (MJC) model [6, 7] has been adopted. The MJC is a phenomenological model and it can be expressed as:

$$\sigma_{eq} = \left(A + B_{eq}^{n}\right)\left(1 + \dot{\varepsilon}_{eq}^{*}\right)^{c}\left(1 - T^{*m}\right) \tag{1}$$

where σ_{eq} is the equivalent stress, ε_{eq} is the equivalent strain, A, B, n, C and m are material constants, and $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_{0}$ is the dimensionless strain rate where $\dot{\varepsilon}_{eq}$ and $\dot{\varepsilon}_{0}$ are the strain rate and reference strain rate, respectively. T^* is a dimensionless temperature given as $T^*=(T-T_r)/(T_m-T_r)$, where T is the absolute temperature, T_r is the room temperature and T_m is the melting temperature.

Material data for the target material (Al6061-T6) have been taken from the Ref. [8] and are shown in Table 1.

Table 1 Material data for Al6061-T6

Density	2700 [Kg/m^3]
Young's modulus	70 [GPa]
Poisson's ratio	0.33
Ref. strain rate	597.2 [s^{-1}]
Melting temp.	893 [K]
A	270 [MPa]
B	154.3 [MPa]
n	0.2215
c	0.0963
m	1.34

In the present research, fracture must be taken into account as well. A modified version of Johnson-Cook fracture criterion [6, 7], which is already implemented in LS-DYNA, was chosen in order to describe the failure phenomenon. JC failure can be expressed as:

$$\varepsilon^{f} = \left[D_1 + D_2 \exp\left(D_3\sigma^{*}\right)\right]\left[1 + \dot{\varepsilon}_{eq}^{*}\right]^{D_4}\left[1 + D_5 T^{*}\right] \tag{2}$$

where $\sigma^{*} = \sigma_m / \bar{\sigma}$ is the stress triaxiality ratio, $\sigma_m=(\sigma_1+\sigma_2+\sigma_3)$ is the mean stress, and $\bar{\sigma}$ is the effective stress or the von Mises equivalent stress ($\sqrt{3J_2}$). Constants D_1, D_2, D_3, $D4$ and D_5 are the constants of this failure model and corresponding values for Al6061-T6 are shown in Table 2 [8].

Table 2 Fracture criterion data for Al6061-T6

D1	- 0.10
D2	0.8396
D3	- 1.174
D4	0.011
D5	1.6

As for the steel ogive-nose bullet, it was modelled as rigid so that the computational time might be reduced. The geometrical details of the projectile are shown in Figure 1 and the corresponding material data are shown in Table 3. The total number of elements of projectile is *37,376*.

Table 3 Material data for steel

Density	*7858 [Kg/m^3]*
Young's modulus	*202 [GPa]*
Poisson's ratio	*0.30*

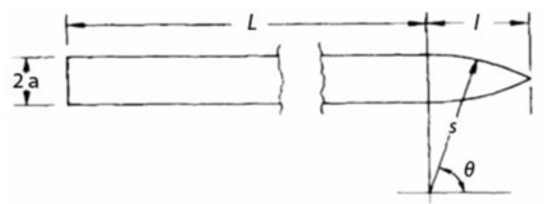

Fig. 1 Geometrical details of ogive-nose bullet: L=67.5 mm, l=21.4 mm, 2a=12.9 mm

In the present paper, the target plate was modelled as *304×152×26.3 mm^3* plate. *8*-node brick elements were used. A convergency analysis, performed to check the mesh effect, was done by taking into account different number of elements across the plate thickness and *565 m/s* as initial velocity, as shown in Figure 2.

Compared against the simulation where 82 elements were used, the simulation which employs 110 elements to model the plate's thickness proved to be more time-consuming. Furthermore, residual velocity changed less than *1%* for the latter simulation. Therefore, *82* elements were used across the plate thickness (Figure 3). The element size is *0.32×0.32×0.32 mm^3* in impact region. Outside the impact region, the mesh coarsens toward the edge of the plate while the number of elements across the thickness was kept the same. The total number of elements for the plate is *5,014,464*.

2.2 Validation of numerical model

Once the numerical model has been described, it is necessary to validate the numerical results by comparing them with experimental ones. Therefore, some experimental data were chosen from literature regarding the normal and oblique impact with different initial velocities. Experimental results of ballistic impact against Al6061-T6 plate [9] were compared to numerical results, as shown in Figures 4 and 5. Residual velocity V_{res} versus initial velocity V_i both from experimental data and numerical results have been fitted using Retch-Ipson model as expressed:

$$v_{res} = a * \left(v_i^p - v_{bl}^p\right)^{\frac{1}{p}} \qquad (3)$$

where *a* and *m* are empirical constants, which are used to fit the data and V_{bl} is ballistic limit. Ballistic limit V_{bl} is obtained by fitting Retch-Ipson model to the numerical and experimental points.

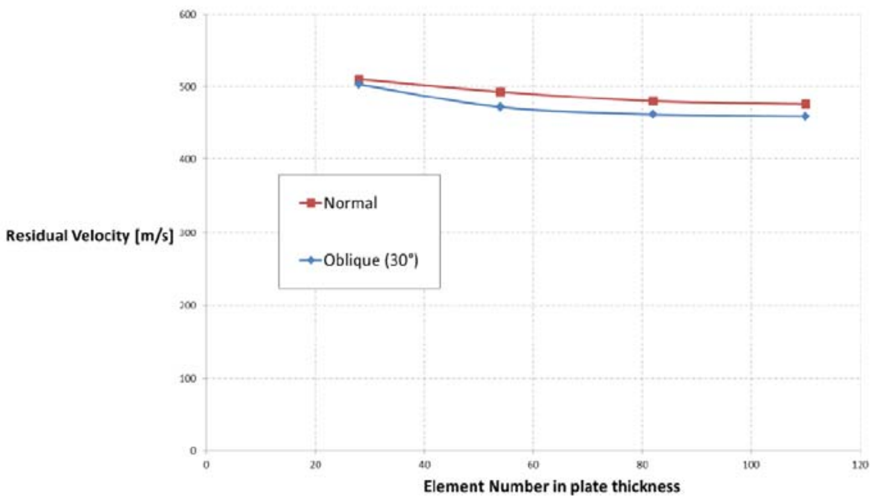

Fig. 2 Effect of number of elements through thickness on residual velocity

Fig. 3 Oblique impact configuration

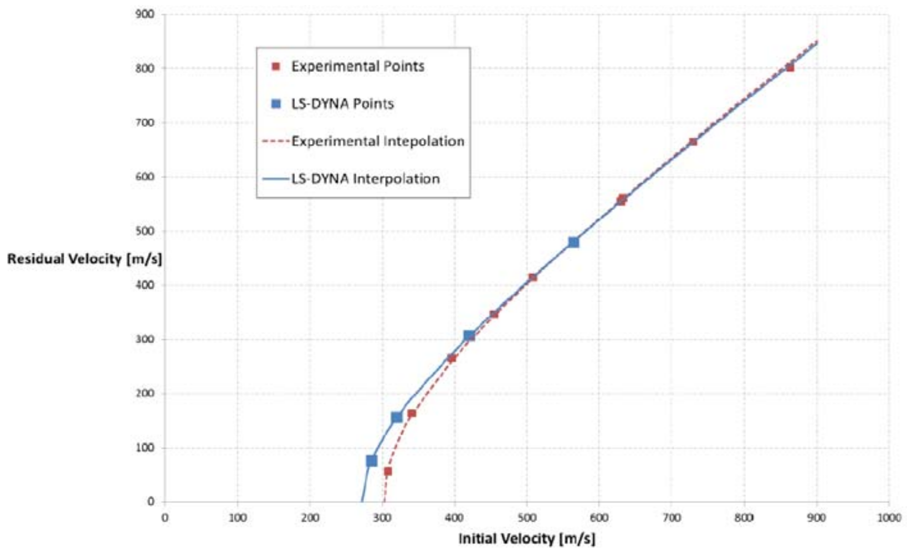

Fig. 4 Validation of numerical analysis for normal impact

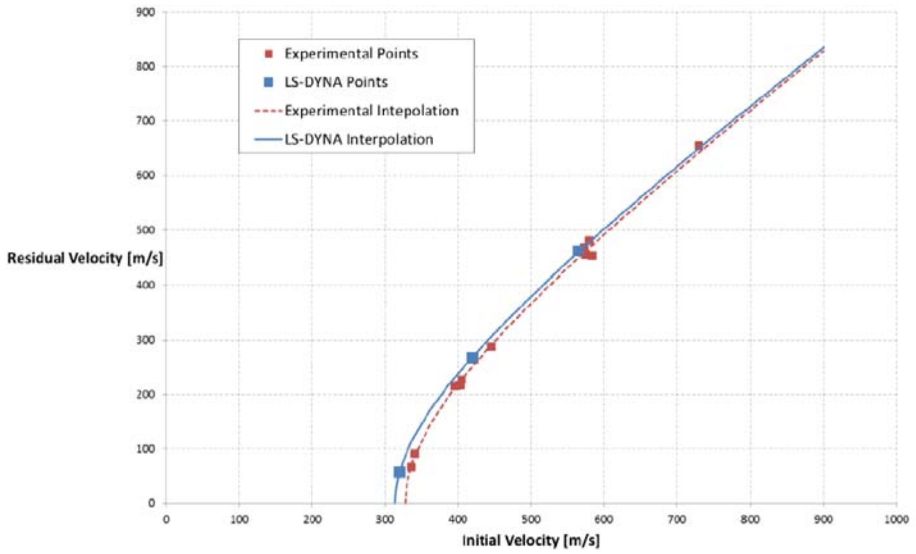

Fig. 5 Validation of numerical analysis for oblique impact (30°)

As it can be seen in Figures 4 and 5, an acceptable difference between numerical and experimental results has been obtained. In other words, taking into account the complexity of event, a very good agreement has been attained between numerical results and experimental data. Hence, the numerical model can be considered very suitable for simulations of such complex scenarios.

2.3 Numerical results

Numerical results for high velocity impact events can be discussed in different ways. Finding the angle limit and effect of ballistic angle are important in such a complex scenario. In the present paper, effect of impact angle on residual velocity is examined at certain initial velocities, shown in Figure 6. In Ref. [10], authors have used the following equation which is able to describe residual velocity as a function of angle for a certain initial velocity:

$$v_{res} = C_2 \left[1 - \left(\frac{\beta}{C_1} \right)^m \right]^{\frac{1}{n}} \tag{4}$$

where, v_{res} is the residual velocity of the projectile and β is the oblique angle. However, boundary conditions are needed to employ this equation in finding other constants (m and n) which are necessary to describe the trend. Moreover, C_1 is the angle when the residual velocity of the bullet is zero. Also, C_2 is the residual velocity when the oblique angle is zero. The parameter C_1 could be difficult to find by means of experimental tests, and therefore affected by uncertainties. In this paper, the following expression has been developed which is able to evaluate the residual velocity as the function of impact angle for certain initial velocity without knowing the angle limit:

$$v_{res} = a * \left(\beta^p - v_i^p\right)^{\frac{1}{p}} \tag{5}$$

Considering *565 m/s* as the initial velocity, the residual velocity is almost unaffected by oblique angle up to approximately *30°* and the residual velocity drop is extensive for a higher oblique angle. However, considering *420 m/s* as initial velocity, there is no oblique angle effect on the residual velocity up to *15°*, however, it drops after a higher oblique angle.

Another important aspect that can be under investigation is finding ballistic limit for different oblique angles. In Figure 7, residual velocity is found as function of the initial velocity for a certain impact angle. The ballistic limit V_{bl} is found by fitting Retch-Ipson model to the numerical points with good reliability.

It can be noticed that the ballistic limit decreases by moving from higher oblique angle to the normal one (Figure 7). Moreover, the investigation into the ballistic limit in a double-layered configuration can be interesting, an issue discussed in detail in the next section of the paper.

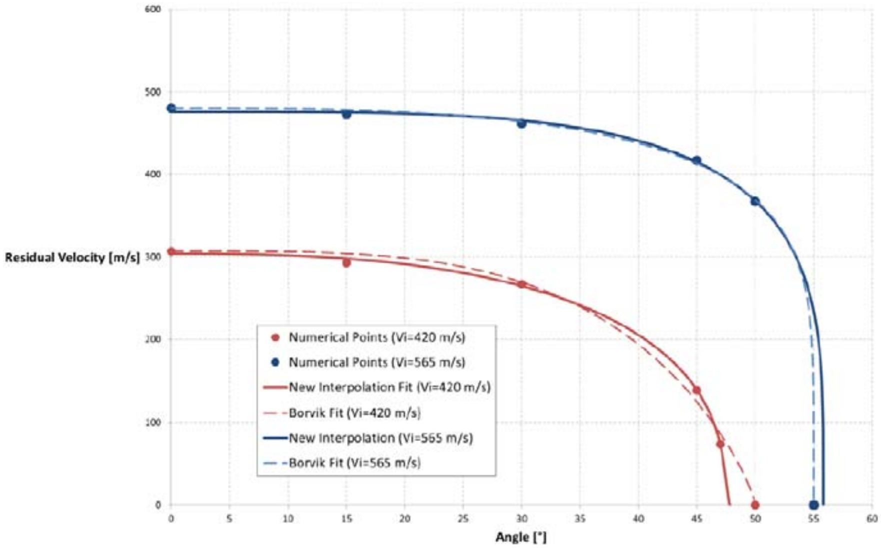

Fig. 6 Effect of impact angle on residual velocity

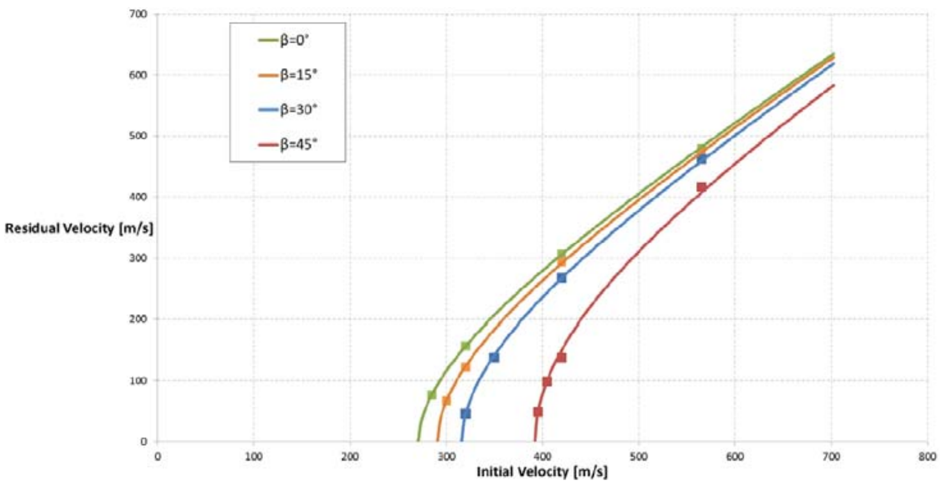

Fig. 7 Residual velocity vs. initial velocity

3. EFFECT OF DOUBLE-LAYERED CONFIGURATION

The purpose of this section is to offer an insight into the effects that double-layered plates with different configurations might have in the event of bullet impact. In recent years, there have been several articles dealing with the effect that double-layered configuration with and without air gap has on a normal impact. However, such studies are rarely conducted for an oblique angle impact, therefore, in this section different cases are under consideration for oblique impact with *30°*. Figure 8 shows a series of model results representing the penetration process of 2×13.15 *mm* double-layered Al6061-T6 plate with *5 mm* air gap, which is penetrated by an ogive-nose bullet with an initial impact velocity of *565 m/s*.

Considering a typical thickness of *26.3 mm*, diverse configurations such as monolithic, double-layered without air gap and double-layered with *5 mm* air gap were under consideration. Numerical results of the mentioned configurations are displayed in Figure 9.

Considering the obtained curves, it is arguable that moving from a monolithic plate to double-layered plates the ballistic limit decreases. Also, by adding *5 mm* air gap between two layers, a further decrease in the ballistic limit is observable.

4. CONCLUSION AND DISCUSSION

In this paper, the effect of oblique impact angle on different target configurations has been evaluated. It has been concluded that the solution having the highest ballistic limit is the monolithic one. The use of a double-layer configuration decreases the ballistic limit. Also, in case there is a *5 mm* air gap between two layers, the ballistic limit decreases even more. This aspect has been already discused in literature for normal impact and ogival bullet [4]. Another interesting aspect regards the angle of impact. It has been shown that increasing the impact angle, the ballistic limit increases as well; hence the most dangerous scenario is the normal one. It is also interesting to evaluate the rebound angle. It has been discovered that the critical angle at which there is rebound is not constant, but it likewise depends on the initial velocity of the bullet. Finally, a new interpolation equation able to describe the curve residual velocity against impact angle has been proposed. The curve is able to fit results in a very good way.

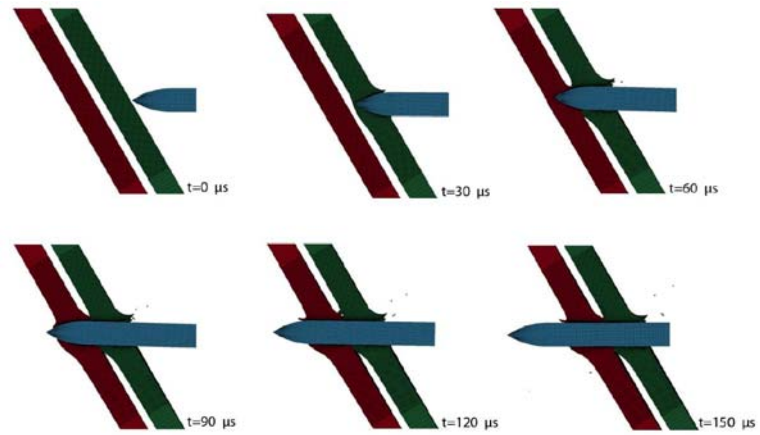

Fig. 8 Double-layered configuration with 5 mm air gap

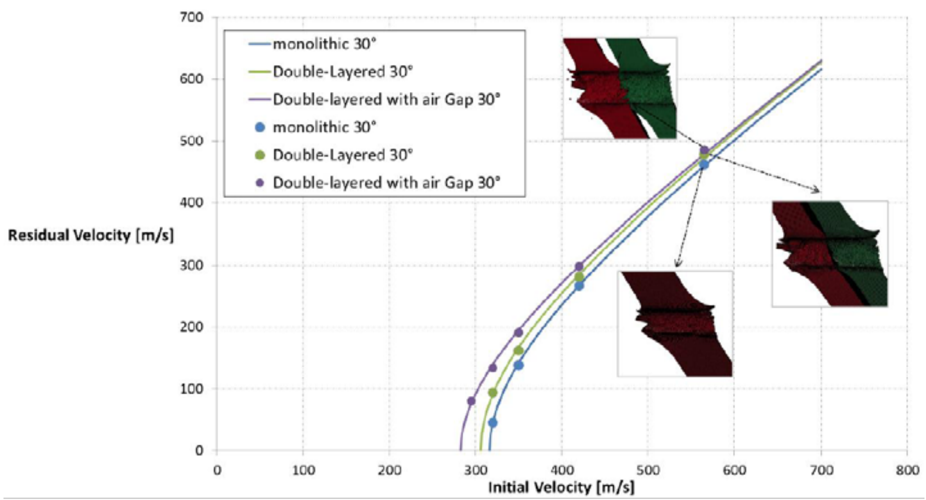

Fig. 9 Residual velocity vs. initial velocity for different double-layered configurations

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NUMERIČKA SIMULACIJA OKOMITOG I KOSOG UDARA O JEDNOSLOJNU I DVOSLOJNU ALUMINIJSKU AL6061-T6 PLOČU

SAŽETAK

Balistička istraživanja načina penetracije metka u metalne ploče te njihova numerička simulacija danas su jedna od suvremenih tema spomenutog polja istraživanja. Unatoč tomu, do sada nemamo kongruentnih rezultata, posebice kada se radi o udarima metka u višeslojne ploče. Naime, sa stanovišta balističkog limita, izbor između slojevitih i monolitnih struktura i dalje ostavlja nedoumice. Također, posljedice uvođenja zračnog razmaka između slojeva metala nisu u potpunosti opisane i razjašnjene. Između ostalog, navedeni problemi su opsežnije ispitani za slučajeve normalnog udara metka (udara okomito na površinu) dok su rezultati za udare metka ukoso s obzirom na površinu malobrojni. Stoga je cilj ovoga rada provesti numeričku analizu kako bi se odredio utjecaj balističkog limita za obje vrste udara u slojevite mete. U tu svrhu bit će korištena provjerena numerička metodologija. Gradivni materijal mete aluminijska je slitina Al6061-T6 čije su mehaničke karakteristike poznate (očvršćivanje, brzina promjene deformacije, razina prekoračenja čvrstoće itd.). Nekoliko modela bit će numerički testirano, a rezultati kritički sagledani.

Ključne riječi: *okomiti udar metka o površinu, kosi udar metka o površinu, numerička simulacija, dvoslojna ploča, zračna praznina, LS-DYNA.*