EPJ Web of Conferences **26**, 04010 (2012)
DOI: 10.1051/epjconf/20122604010

Investigation about the influence of the mechanical properties of lead core and brass jacket of a NATO 7.62 mm ball bullet in numerical simulations of ballistic impacts

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Abstract. In the present work a validated numerical approach has been used in order to build a robust and reliable FE model of the impact of a NATO 7.62 mm ball bullet, against an aluminium transmission shaft. The bullet is a full metal jacket type, with a lead alloy core and a brass jacket. Target shaft is made by an Al6061-T6 aluminium alloy. According to the soft core (lead alloy) of the bullet, most effort has been spent in order to evaluate the effect of bullet materials mechanical properties on the numerical results. Numerical analyses, carried out using the non-linear dynamic finite element solver Abaqus\Explicit 6.10, have been performed focusing on core and jacket material behaviour (target material, Al6061-T6, has been previously calibrated by the authors). Thus numerical analyses have been performed considering for the mechanical behaviour of the bullet both a simplified approach (as reported in literature) and new material data (with strain rate effect) obtained by means of experimental tests on the two materials (lead and brass) with specimens cut directly from the bullet. Finally the results of the analyses have been compared with real experimental ballistic tests.

1 Introduction and experimental tests

Reliable numerical simulations of ballistic impact are an actual task especially when deformable bullets are considered. Several critical components are exposed to the risk of ballistic impacts and the capability to perform robust and validated simulations is fundamental to predict the phenomena and eventually to improve the strength of the components. In order to obtain reliable results from numerical simulations of extreme loading condition like ballistic impact, the use of accurate material behaviour inside numerical models (constitutive laws and damage criterion) is required, both in terms of strength model and ductile fracture. Generally, calibration of material is focused on target material due to the fact that projectile is often a rigid body. However the 7.62 NATO ball 9.5 g projectile is a commonly used ammunition and consists of a soft core of alloyed lead. The behaviour of such type of projectile is very dangerous for thin aluminium structures (after impact the soft core tends to mushroom-shaped). It is therefore crucial to evaluate the mechanical behaviour of bullet materials in order to increase the reliability of related numerical simulations. As underlined below in this paper, the main problem in achieving this goal is the limited availability of material data of the projectiles. A deformable model of a NATO 7.62 projectile has been introduced in recent studies. Chocron [1] studied the impact of a NATO 7.62 APM2 into thin aluminium plates. In [1], simple constitutive laws were used for both target and projectile materials and numerical results are not completely in accordance with experimental relieves. Furthermore Nsiampa [2] studied the impact of NATO 7.62 mm into Al-5083 plate targets. In [2] finite element simulations were carried out using the hydrocode AUTODYN.

The numerical investigation developed in the present research have been started and validated on the basis of experimental data obtained in a previous study [3]. In this campaign experimental ballistic tests have been performed shooting against aluminum Al-6061-T6, 1.65 mm thick, 63.5 mm diameter pipes. Specimens have been provided with flanges and specifically designed supports in order to place them in the correct position. NATO 7.62 mm ball, Full Metal Jacket bullets have been used. This kind of projectile has a lead-antimony alloy core and a brass jacket. Several placements have been tested in [3] at 0° and 45° degrees of the angle of obliquity. However it is important to highlight that nominal impact conditions can slightly vary compared to the real ones. The main causes of the variability can be attributed to external ballistic factors [4], produced by aerodynamic effects on the projectile. This situation is clear looking at figure 1. This tube has been nominally impacted on the longitudinal shaft axis (therefore in the center on the pipe section) and with a trajectory normal to it, figure 1(a). Analysing damage shape, it can be seen that entry and exit holes are not circular but they indicates that bullet impacted tube with a not null total angle figures 1(b), 1(c). [6,7]

2 Numerical models

The numerical model used in present research is a further development of the one built in [7]. Numerical simulations have been carried out using the finite elements commercial software ABAQUS 6.10 and an explicit framework. Three different parts are involved into impact: the aluminium shaft, the lead-antiminy core bullet and the brass jacket of the bullet. Brick solid elements with reduced integration and enhanced hourglass control have been used for the

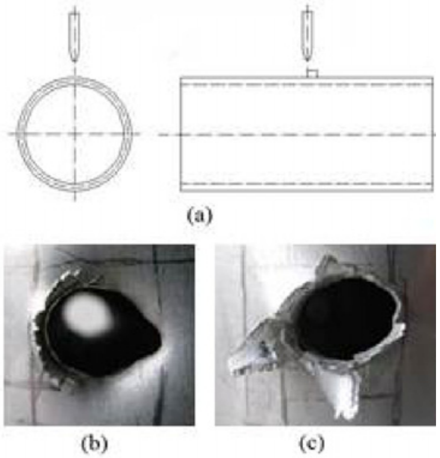

Fig. 1. a) Nominal impact condition, b) entry hole, c) exit hole.

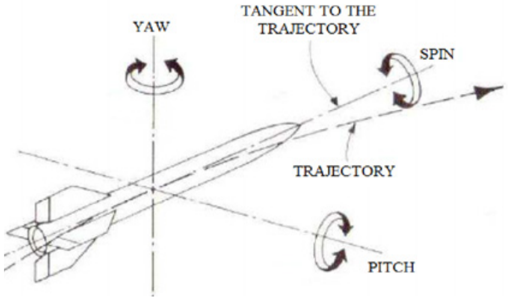

Fig. 2. Projectile orientation in the space.

mesh of the impact area (element type: C3D8R). For the impact region a very refined mesh have been used with elements having dimensions of 0.25 × 0.25 × 0.25 mm. For what concerns the constrains of the shaft, two different constrains have been applied at the end of the shaft. At one end, the displacements of the nodes in all three directions are fixed. At the other termination, only two translations are blocked, leaving the other, directed as the shaft's axis, free.

As already stated projectile consists of two parts: jacket and core. Hence also its numerical model has been made reproducing these two parts using brick solid elements with reduced integration and enhanced hourglass control. The elements mean dimension is 0.269 mm for the jacket and 0.26 mm for the core. Initial velocity and spin have been associated to the global bullet model. The value of the initial translation velocity is 860 m/s and the spinning velocity is 78.5 rad/s. A very important aspect regards the choice of the trajectory parameters. On the basis of the results of [7] a yaw angle of 2.26° and a pitch angle of 2.26°, figure 2 have been chosen.

A general contact algorithm has been defined to simulate interaction between parts and friction has been neglected. In order to reproduce damage, element deletion and nodal erosion have been activated. It has been also adopted a distortion control in order to guarantee the correct termination of the analysis nevertheless the presence of high distorted elements.

Moreover effect of temperature on components has been included.

Table 1. JC parameters for Al6061-T6 target material.

A	B	n	C	$\dot{\varepsilon}_0$	m	T_a	T_f
[MPa]	[MPa]	-	-	[s^{-1}]		[K]	[K]
270	154.3	0.2215	0.1301	597.2	1.34	294	925

Table 2. BW fracture locus analytic functions Al6061-T6 target material.

Triaxiality $\eta\,(\sigma_h/\sigma_{vm})$	Equation	Coefficients
$\eta < 0$	$\varepsilon_f = A/(\eta + 1/3)$ $-3A + \varepsilon_{ftp}$	$A = 0.428$; $\varepsilon_{ftp} = 0.474$
$0 < \eta < 0.0223$	$\varepsilon_f = m\eta + q$	$m = 20.85$; $q = 0.474$
$0.0223 < \eta < 0.0626$	$\varepsilon_f = m\eta + q$	$m = -5.43$; $q = 1.06$
$0.0626 < \eta < 0.37$	$\varepsilon_f = m\eta + q$	$m = -0.848$; $q = 0.774$
$\eta > 0.37$	$\varepsilon_f = A/\eta$	$A = 0.17$

2.1 Material data

A crucial aspect of numerical analyses regards the material calibration of the material involved in the simulation. In present case target material is aluminium alloy Al-6061-T6. The properties of this material has been calibrated in [8,9]. As constitutive law the Johnson-Cook (JC) [10] has been chosen. This constitutive law can take into account strain rate and temperature effect. The chosen constitutive law form can be seen in Eq. (1)

$$\sigma = [A + B(\dot{\varepsilon}_p)^n][1 + C\ln(\dot{\varepsilon}_p/\varepsilon_0)]$$
$$[1 + (T - T_a)/(T_f - T_a)^m] \tag{1}$$

In Table 1 material data for the target shaft have been summarized.

Another important numerical choice regards the fracture criterion [11]. In present research a ductile criterion has been adopted. This kind of approach is based on the definition of a fracture locus curve which describes the failure strain as a function of stress triaxiality. Data have been calibrated in [8] and have been summarized in Table 2. This criterion describes the condition when an element fails (damage initiation); in present work also a damage evolution has been adopted. The evolution in the damage has then been specified in an exponential form through the definition of G_f, the energy needed to open a unit area of crack, evaluated as proposed in [12] and equal to 11.2 J/mm^2.

However the focus of the present research regards the use of a dedicated material calibration of projectile materials compared with previous work [6,7].

Accordingly with [4–6] there is a lack of data from both bibliography and manufactures thus in previous analyses only simple constitutive law and fracture criterion have been used. As far as concern the former data, for the material of the jacket (brass) elastic-plastic behaviour, defined for two points is used, while for core (lead-antimony),

Table 3. Former projectile properties [7].

Part	Young Modulus [GPa]	Yelding Stress [MPa]	Ultimate Stress [MPa]	Strain at failure ε_f
Core	16	32	32	31%
Jacket	115	385	455	5%

an elastic perfectly plastic material has been defined. A ductile failure criterion with a constant ε_f at different triaxiality has been chosen for both two materials. Mechanical properties have been obtained by means of chemical composition identification and hardness tests, Table 3. Instead in present research improved material data have been used from a specific experimental campaign based on specimens made directly from lead and brass alloys of core and jacket obtained one step before the final manufacturing of the bullet [14]. Formers projectile data collected from [7] have been summarized in Table 3. Present research new projectile data have been summarized in Table 4 [14].

It is worth to mention that the data in Table 4 are not exactly the data reported in [14] but are very similar. The data in [14] are the last step of an optimization process; the data in Table 4 belong to an intermediate step.

However the data in Table 4 are more representative of the real material properties (including strain rate and temperature effect before neglected) respect of the former data reported in Table 3.

In particular as constitutive law it has been chose a JC one and also strain rate effects have been taken into account. Constant fracture, function of triaxiality, has been used and the fracture strain level has been updated adopting new values coming from the recent experimental campaign.

3 Results

A semi quantitative comparisons of the results have been carried out in order to assess the goodness of the model and the effect of different bullet material calibration on the numerical simulation of the whole impact. Focusing on the 90° impact, to compare numerical and experimental results (regarding the damage shape of entry and exit holes), a Matlab® script file developed in [6] has been used. This script is able to build graphically on a plane graph the entry and exit hole shapes both using numerical and experimental data. In this case the acquisitions of the experimental holes shape have been carried out using a Reverse Engineering (RE) technique [6,7]. In figure 3 it is possible to see the differences between the numerical profile and the experimental one. Indeed while the entry experimental profile is very regular, the exit one presents a significant petalling phenomenon. This makes even the RE acquisition data difficult to elaborate due to the high sharp profile. However the Matlab script appears to be able to recognize at a reasonable level this complex shape thus making a satisfactory semi quantitative comparison possible.

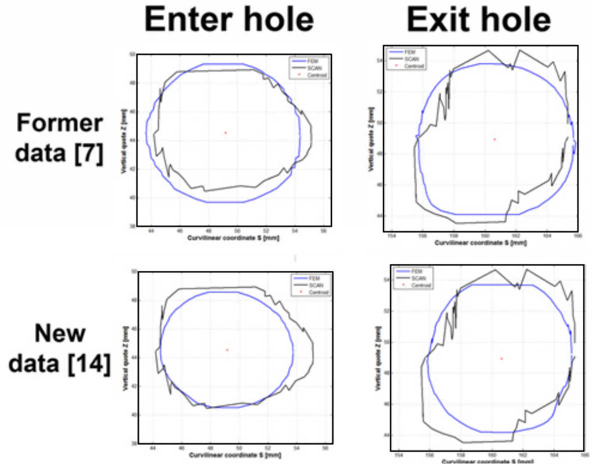

Fig. 3. Damage profile comparison between numerical and experimental data with the new and former materials properties for bullet.

In addition, especially for the exit holes it is very significative a qualitative photographic comparison in order to evaluate the petalling behavior. Comparisons have been made between numerical and experimental images of damage holes. These comparisons are reported in figure 4.

The new material slightly increase petalling on the exit hole making the new simulation more similar to the experimental case, however the differences are very reduced. On the contrary it is clearly evident from Fig. 3 that the former calibration better represents the holes in terms of area. This behavior can be explained looking at Figure 5 where the model of the bullet after the impact is reported. In this type of impact, the behaviour of the jacket drives the simulation and the increase of strain at failure of the brass jacket (from 5% to 40%) cause a sensible decrease of the damage involving the jacket.

This slightly limits the contact of the soft lead core (that tends to spread during the contact) with the pipe reducing the damaged area, figure 3. Also considering the residual velocity of the bullet the authors obtain 771 m/s from experimental test, 778 m/s from numerical former data [7], 806 from numerical new data [14]. Again the reduce damage of the jacket, obtained during numerical simulation with new data [14], increases the residual velocity of the bullet.

It is interesting to test the new materials calibration for the 45°, tangent impact. In this case the impact involves a wider area of the pipe thus the jacket is largely damaged (eroded) allowing the lead-antimony alloy to impact against the pipe. In this case the result is really impressive. The former calibration are not able to reproduce completely the large damage (with several petals) obtained during experimental tests, figure 6. On the contrary the new material calibration and in particular the new calibration of the core better reproduce the behavior of the bullet, figure 6.

When the bullet hits the pipe the thin jacket is quickly eroded (thus difference in jacket calibration are almost negligible) and the soft core is able to deform and to damage the pipe. Also as far as concern residual velocity, experimental residual velocity acquired is 718 m/s,

Table 4. New projectile properties [14].

Part	Constitutive equation	A	B	n	C	$\dot{\varepsilon}_0$	m	T_a	T_f	Locus Locus	Strain at Failure ε_f
-	-	[MPa]	[MPa]	-	-	[s^{-1}]	-	[K]	[K]	-	-
Core	JC	0	55.552	0.0987	0.2312	72.108	1	294	600.4	Constant strain to failure	31%
Jacket	JC	90	628.03	0.7201	0.2659	745.82	1	294	1288	Constant strain to failure	40%

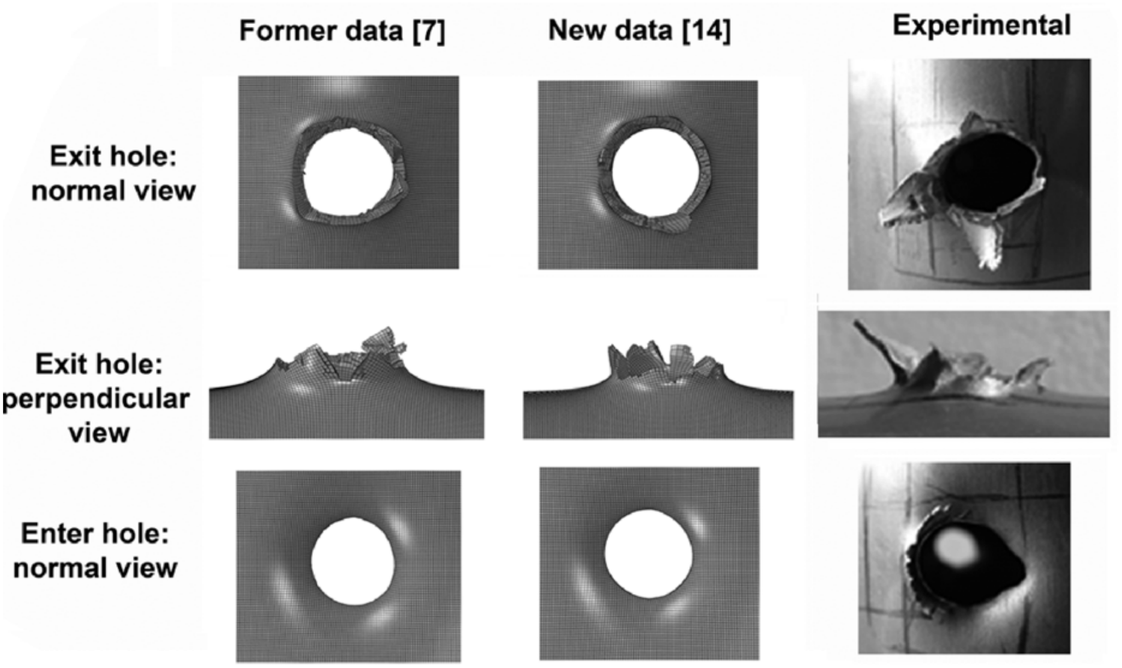

Fig. 4. Qualitative numerical\experimental comparisons between entry and exit holes using former bullet material data [7] and the new ones [14].

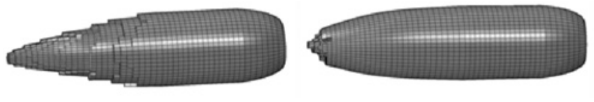

Fig. 5. Numerical bullet conditions after impacts, on the left with formers material data [7], on the right with the new data [14].

numerical with former calibration 757 m/s, numerical with new calibration 719 m/s. The importance of a correct calibration of mechanical properties of the bullets materials is therefore highlighted.

4 Conclusions

In present paper the effect of a dedicated material calibration of the mechanical properties of a soft core bullet has been evaluated on the results of Finite element model of impact events. The new calibration [14] increases the goodness of the results but, at present, only when the lead-antimony alloy core is deeply involved. Experiments [3] have shown that oblique impact generates larger damage holes than normal ones. In this situation also bullet suffers a significative deformation and erosion, thus the use of an improved material model (that include hardening, strain rate/temperature effect and failure) lead to a good accuracy in simulations, Fig. 7. In particular the present investigation shows the importance of the lead core characterization in case of huge deformation and erosion of the bullet: in this case the lead core drives the whole simulation.

On the contrary, direct impact (90°) shows that the new characterization of the brass is not satisfactory and the results highlight that probably the 40% value of strain at failure is not correct (overestimated). It is possible to explain this behaviour considering that brass mechanical behaviour has been obtained [14] from specimens cut from a plate. These specimens are representative of an intermediate state of the material before to be processed in order to obtain the jacket of the bullet. This process is characterized by large metalworking therefore part of the ductility of the material can be “consumed”. Thus a strong reduction in the strain at failure of the brass is possible.

Further analyses are necessary directly on the jacket of the bullet in order to better calibrate its behaviour. However, at present, as previous underlined, the results for the 45° degree impact are really improved. In this case the thin jacket is less influent and the goodness of the new calibration of the lead core is clearly visible.

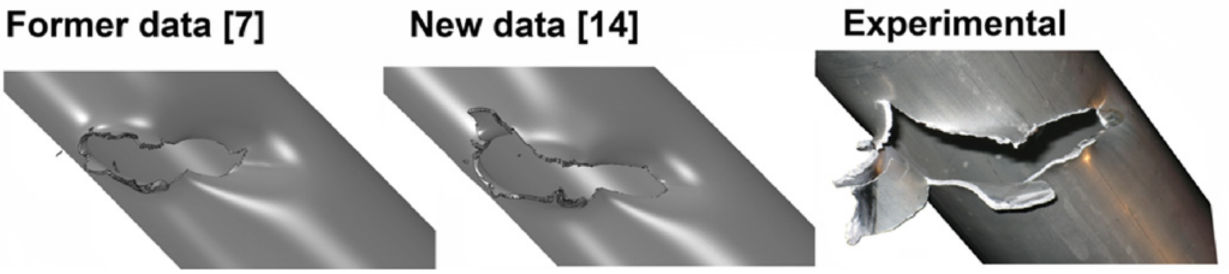

Fig. 6. Final numerical impact hole for a 45° impact condition using former projectile characterization [7] and the new one [14].

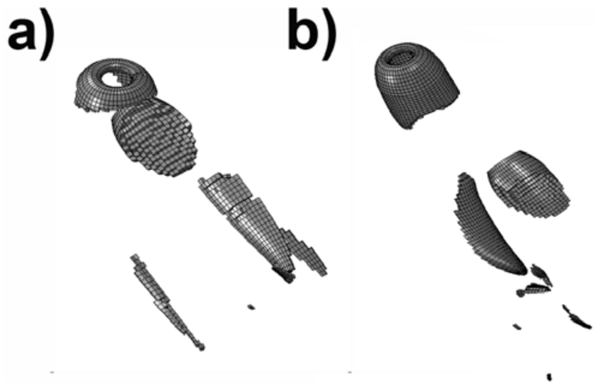

Fig. 7. Final numerical bullet conditions for a 45° impact using former projectile characterization [7] a), and the new one [14] b).

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