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An experimental–numerical investigation on aluminium tubes subjected to ballistic impact with soft core 7.62 ball projectiles

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ABSTRACT

An experimental–numerical investigation of the ballistic impact of 7.62×51 mm soft-core ball 9.5 g projectiles on aluminium tubes is presented in this paper. The tubes are made of Al-6061-T6 and simulate actual components of a helicopter tail rotor drive shaft. Several tests have been carried out: a real gun has been used to produce ordnance velocities and a dedicated support frame has been built to perform impact tests with an angle of obliquity (in order to reproduce the most critical damage on the component that is subjected to torsional service load). Initial and residual velocity of the bullets, shape and dimensions of the damage, and the residual stresses on the components, have been measured.

Numerical models of the impact have been developed with the commercial Finite Element code ABAQUS/Explicit. The Johnson–Cook (JC) constitutive model and the Bao–Wierzbicki (BW) ductile fracture criterion have been calibrated for Al-6061-T6 and have been used for the analyses. The effect of the bullet type on the damage has been investigated; therefore the ball bullet has been fully modelled (core and jacket) to highlight the effect and danger of this type of soft core bullet in case of impact against aluminium thin structures. Numerical models are in good agreement with the experimental results; more specifically they show a satisfactory capability to reproduce the residual velocity of the bullets and the failure mode, as well as the residual stress fields on the tubes near the damaged zone.

1. Introduction and motivation

While a large number of publications study the impact of a rigid projectile (often hard steel rods) on a plate for ballistic protection, thereby focusing on the ballistic limit, very few studies consider the impact of real deformable projectiles on mechanical functional components and, in particular, on aluminium tubes; moreover an analysis of the damage shape and the residual stress pattern is often missing. Aim of this paper is an experimental–numerical study of the impact of a 7.62×51 mm soft-core ball 9.5 g projectile striking tubes, representing a helicopter drive shaft, at ordnance velocity (the usual velocity of such conventional bullets). Starting from arguments by the literature survey presented in Section 2 and in accordance with the tubular shape and torsional load applied on the real components, a critical condition for the specimens, in terms of impact parameters, is identified, in Section 3. Experimental ballistic tests are reported in Section 4 and particular emphasis is paid to the variation of results. The tubular shape of the target, the obliquity of the impact (as underlined in the following, oblique impacts are the most critical for such types of components) and the soft, thus very deformable, core of the bullet makes the damage shape obtained very complex and variable even if the impact conditions for the majority of the experimental test programme is kept nominal. A numerical methodology able to correctly reproduce the damage caused by the ballistic impact (in terms of shape and the extension of the damage, the residual stress field and residual velocity) is hereafter presented in Section 5 with focus on the material constitutive laws used during the numerical analyses.

2. Background

Investigations on ballistic impact against functional components are not frequent in the literature; especially for conditions that differ from normal impact and involve deformable bullets. However the more general ballistic impact data, extensively analysed in the literature has been exploited for the present work. In Backmann and Goldsmith [1] and Goldsmith [2] a wide range of impacts and some important ballistic definitions and concepts are discussed. A detailed and extensive study referred to steel plates has been carried out by Børvik et al. [3,4] and Dey et al. [5]. The influences of the target characteristics, like the material and its thickness, and of the projectile type on the impact phenomenon are highlighted. Oblique impacts on plates are instead experimentally and analytically studied in Gupta and Madhu [6] and Iqbal et al. [7].

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Forrestal and Piekutowski [8] and Piekutowski et al. [9] and Roisman et al. [10] have conducted a complete set of experiments at different impact speeds and projectile shapes with aluminium plates made of Al-6061 alloy. Warren and Poormon [11] have considered an angle of obliquity for the experimental tests. Other experimental studies on aluminium plates can be found in Gupta et al. [12] and Kezhun and Goldsmith [13], where also tumbling projectiles are considered. Several of these works increase also the understanding of the behaviour of Al 6061 alloy, but they fail to take into account the use of a real bullet and they do not completely address the issue of the target shape under investigation, i.e. a tubular profile.

Zhang and Stronge [14], and Zeinoddini et al. [15] addressed issues similar to the work presented in this article. In the first paper, analysing impacted blunt projectiles on mild steel tubes at various obliquity angles, their influence on the type of the rupture produced was studied. The second work, on the other hand, analysed the behaviour of axially pre-loaded struck steel tubes, to study their dynamic failure. In both of these studies a specific missile impactor, quite different from deformable bullets, was specially designed.

Systematic studies with real projectiles are not commonly published in the literature. Børvik et al. [16] developed both experimental tests and numerical analysis of the impact of 7.62 mm AP (armour piercing thus hard core) and ball (soft core) types against 5 different high-strength plates. The experimental results are interesting, showing the perforation resistance of five different steels hit with small arm bullets. The FE results highlighted some discrepancy concerning the numerical simulations of a soft-core bullet against a hard plate due to severe mesh distortion. The numerical simulation for an AP bullet was not hindered by numerical problems and reasonable agreement with the experimental data was obtained. Also Hazell et al. [17] conducted a series of impact tests of a soft-core 7.62 mm ball into glass-faced transparent elastomeric resin to investigate the penetration and the cavity shape. They also carried out FE analysis that showed an acceptable correlation with the impact test results. Another point to remark on, as far as experimental tests with small bullets shot by a real firearm are concerned, is the aerodynamic effect on the projectile. These external ballistic factors can be summarised as a deviation from the aimed trajectory with yaw and pitch impact angles unequal to zero. Values were measured and reported in Hazell et al. [17] and Piddington [18].

In order to obtain reliable results from numerical simulations, the use of an accurate material behaviour inside numerical models (constitutive laws and damage criterion) is required. Comprehensive models of the material behaviour are widely described in the literature. One of the most famous and widely used models is the Johnson–Cook (JC) model [19]. Although it is quite dated, it has proved to be particularly valid, reliable and simple for the calibration of the hardening behaviour where the effect of strain, strain rate and temperature are uncoupled. However, as far as the ductile fracture is concerned, various formulations and approaches have been proposed, used and calibrated for impact simulations: Wierzbicki et al. [20], Teng and Wierzbicki [21] Dey et al. [22], JC [19]. The JC model has some limitations, but can ensure quite valid engineering results as demonstrated in Dey et al. [22]. However, in 2004, Bao and Wierzbicki proposed an innovative model for ductile metal alloys, the so called Bao and Wierzbicki [21,23], which has the advantage to cover fracture behaviour in a wide range of stress triaxiality. Recently more complete criteria covering all possible loading cases have been presented, Bai and Wierzbicki [24,25]. However, the Bao and Wierzbicki [23] model is easy to calibrate and implement in a commercial numerical solver. It has a good geometrical transferability and has been proven to be able to accurately predict ductile failure both for ballistic impact [21] and also for complex loading cases, Viganò et al. [26,27]. A comprehensive JC model including plastic flow and strain rate effect and the Bao–Wierzbicki fracture model have been previously calibrated [28,29] for the target material, Al-6061-T6, and the results are briefly presented and exploited in this work.

Moreover, to increase the reliability of numerical simulations to predict an actual ballistic impact with real bullets, modelling of a deformable projectile is increasingly considered. 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 soft-core 7.62 projectile has been introduced in recent studies. Chocron et al. [30] studied the impact of a 7.62 APM2 into thin aluminium plates whereas Nsiampa et al. [31] studied the impact of soft-core 7.62 mm AP into Al-5083 plate targets. In that work, simple constitutive laws were used for projectile materials following the approach of Hazell et al. [17].

3. Experimental set-up

The target specimens consist of a 760 mm long thin walled cylindrical shaft, made of Al 6061-T6 with an external diameter of 63.5 mm and a thickness of 1.7 mm.

The projectile used for the tests is an ogive nosed soft-core 7.62 × 51 mm ball. It is a *full metal jacket* bullet, with a brass coating and an alloyed lead core, see Fig. 1(a). Ogive nosed projectiles are the most efficient penetrators of plates of reduced thickness (about 1.5 mm) as found in Gupta et al. [32] although the penetration power of a soft core ogival nosed projectile is reduced compared to an armour piercing type. Nevertheless due to its core deformability it can cause wide-ranging damage on thin walled structures, especially in case of multiple penetrations or a semi-tangential trajectory.

The chemical composition of the bullet material has been evaluated using Scanning Electron Microscopy (SEM). The results and the main characteristics of the projectile are summarised in Table 1. The core of the bullet is built in lead (Pb) alloyed with

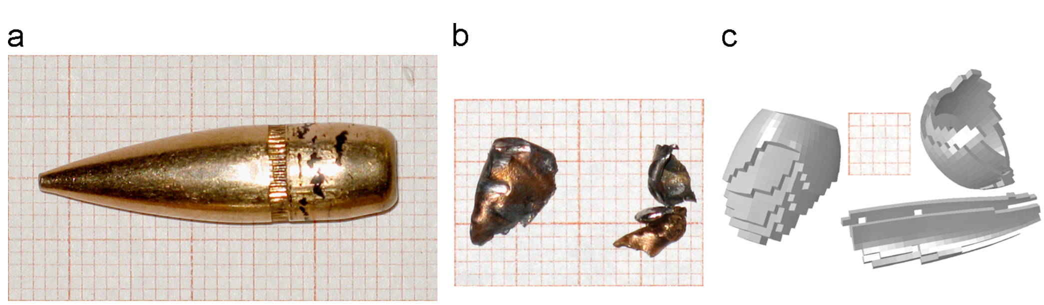

Fig. 1. (a) Soft-core 7.62 × 51 mm full metal jacket 9.5 g ball bullet, (b) real projectile recovered after an impact test, (c) deformable projectile at the end of the numerical analysis.