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Experimental study of the coupling parameters influencing the terminal effects of thoracic blunt ballistic impacts

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ABSTRACT

The objective of the study is to better understand how blunt projectile ballistic parameters and material properties influence the events leading to injuries. The present work focuses on lateral thoracic impacts and follows an experimental approach.

The projectiles are made with a soft foam nose assembled with a rigid rear plastic part.

The dynamic properties of the foams were first determined using the Split Hopkinson Pressure Bar (SHPB) system. The impact forces on a rigid wall were then measured to provide reference load data. Lastly, shots were made on isolated thoraxes of porcine cadavers to investigate the response in the vicinity of the impact (wall displacements, rib accelerations and strains, rib fractures). Results show that the severity of the response appears to be mainly correlated with the impulse and with the pre-impact momentum.

1. Introduction

Less-lethal kinetic weapon projectiles (LLKW) used in riot or crowd control are designed to incapacitate without causing serious injuries. Unfortunately, LLKW are not harmless. The literature reports numerous injuries and also some deaths related to shots by 40 mm hybrid ammunition (that is, with a foam nose and a plastic base). Ballistic blunt thoracic trauma, including behind armor blunt trauma or thoracic impact from a large LLKW projectile such as a 44 mm "Flash-Ball" or 40 mm hybrid rubber bullet, may cause severe physiological dysfunctions and physical damage. For example, skin lesions, rib fractures, heart and pulmonary contusions have been reported as injuries in Refs. [1–6].

LLKW are defined by a lower limit of efficiency and an upper limit of injury level. In order to fulfill this requirement, substantial research has been undertaken over the past four decades to better understand injuries resulting from the blunt impact of these projectiles on the human body. Each part of the body possesses its own response which requires specific studies for each region of interest. The present work focuses on the thoracic response and some associated injuries.

Rigid projectiles were used by most of the previous authors (in particular: [7–9]) in order to analyze how the projectile kinetic energy (E_c, the projectile mass times the square of its velocity) or the local thoracic response are related to the injury level. In these investigations, PMHS (post mortem human subjects) or animal surrogates were used [7]. Living animal surrogates enable the assessment of pathophysiological responses to the impacts. To understand the animal response, some authors have developed physical models in order to compute physiological data, e.g. the intracranial pressure [10], under blunt impacts. By predicting the biomechanical responses of living animals based on surrogate tests animal experiments also provide insight for controlling the differences between living humans and surrogates when developing response and injury targets. Live porcine and PMHS responses to blunt impacts of LLKW have been analysed and compared using wound criteria by [11]. Sondén et al. [12] used Swedish landrace pigs, protected by a ceramid/aramid body armor which were shot with a standard 7.62-mm assault rifle; morphological injuries, cardiorespiratory and electroencephalogram changes as well as physical parameters were registered. Additional references include: [3,13]. Cooper and Maynard [9] studied impacts to the

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lateral thoracic wall (TW) of anaesthetized pigs with a 37 mm PVC cylinder in the range 68–220 J. To assess the TW displacement, they digitized images of the rear of the projectile, assuming that the projectile does not deform. This method, also used by [14] is valid only for projectiles considered as rigid when compared to the stiffness of the biological structure. Bir et al. [8] used PVC baton impactors launched on human cadavers. The body response was characterized by the impact force measured by an accelerometer mounted on the rear impactor side. The results define corridors in which a load force to a given impact is recorded.

The experiments show that thoracic deflection is an interesting parameter for predicting skeletal injuries. According to [9,15], the local chest deflection is correlated to the kinetic energy and momentum (Q_0, the projectile mass times its velocity). However, investigations were exclusively performed with the "plastic baton".

Nsiampar et al. [16] demonstrated that if only the kinetic energy is considered, the effects of deformable projectiles cannot be compared, and therefore that kinetic energy is insufficient to define an injury criterion.

Just after impact, the load force increases while the displacements are very small. Secondly, large displacements take place which may last long after the contact with the projectile has vanished. Injuries frequently revealed by the autopsy include rib fractures or tissue tearing, etc. Hence, two states may be distinguished: before any fracture, and after that, a weakened structure, where the risk of pleura and lung perforation by broken ribs becomes significant.

Prat et al. [11] studied the injuries observed on porcine models impacted by 40 mm less lethal projectiles, with kinetic energies of 100–160 J. The projectiles used by [11] were similar to those of the present study but they were not characterized. Analyzing the data of these authors [17] highlighted that Q_0 and the projectile design influence the skeletal motion and energy transfer. In addition, Pavier et al. [17] clearly reproduced the experimental trends with a finite element model, which allowed us to go even further by stating that the thoracic displacement correlates with the transmitted impulse.

However, confirming this statement required further investigations, involving accurate knowledge of the projectile behaviour and of the instantaneous state of the structure.

We therefore conducted experiments to analyze the influence of the ballistic parameters and the projectile material properties.

The biological surrogates were isolated porcine cadaver thoracic cages. The analysis was based on redundant data acquisitions, and was also aided by dynamic finite element models to verify that some hypotheses were correct.

Three 40 mm projectiles were specially designed. In Section 2, the characterization of the foams and the determination of the impact load on a rigid wall are presented. In Section 3, the methods for studying impacts on porcine cadaver rib cages are described. This is the biological surrogate of choice due to its biomechanical similarity with the human chest.

Results include: (i) impulses transmitted during the impacts, (ii) time and space distribution of the response and (iii) the time of the rib fracture. The analyses are presented in Section 5.

2. Characterization of the materials and of the projectiles

2.1. Constitutive material law of the projectile nose foam

The foams are made of a polychloropren basis, with a mass density varying between 560 and 940 kg/m^3. They include closed-micro cells of sizes within 50 and 100 μm. Their chemical formulations were adjusted so that the property range includes that of foams which are part of existing LLKW projectiles used by the law enforcement authorities. We proceeded iteratively, until the desired stress–strain curves were obtained, both in the dynamic and in the quasi-static domain. Three chemical formulations labeled **21**, **22**, and **23** were designed for the present study.

In the *static range*, traction-compression tests of the samples were applied to obtain the longitudinal strain under a monitored axial stress σ.

The undeformed and deformed lengths are ℓ and ℓ_0, respectively; S_0 is the sample cross-sectional area.

In the *dynamic range*, the SHPB was used to identify the material constitutive law for strain rates between 250 and 800 s^{-1}. The sample is placed between two bars (the "input" bar and the "output" bar). The principle of the test is to generate a crenel of compressive elastic wave which is created by an impactor launched on the input bar. The crenel duration is determined by the round trip times of the compressive waves in the impactor. Starting at the impacted side, the waves travel in the bar towards the sample. After the wave crenel has reached the sample-bar interface, part of it is reflected, and the other part is transmitted to the output bar. Processing of the data required the strain histories measured on the two bars by two strain gages. Gage 1, on the input bar, provides the incident and reflected strains vs. time t, $\varepsilon_i(x_1, t)$ and $\varepsilon_r(x_1, t)$, respectively. Gage 2, on the output bar, provides the transmitted strain, $\varepsilon_t(x_2, t)$. If the bar material is *purely elastic*, (e.g. aluminium or steel) applying the formula describing the wave propagations would lead to the dynamic variables at the sample interfaces (indexed "*e*" for input, "*s*" for output), namely particle velocities v_e, v_s; reaction forces F_e, F_s. Denoting respectively E_B, ρ_B, and S_B, the bar Young modulus, mass density and cross-sectional area, the wave velocity is $c_B = \sqrt{E_B/\rho_B}$, and:

$$v_e(t) = -c_B[\varepsilon_i(x,t) - \varepsilon_r(x,t)] \quad (1)$$

$$F_e(t) = E_B S_B[\varepsilon_i(x,t) + \varepsilon_r(x,t)] \quad (2)$$

$$v_s(t) = -c_B\, \varepsilon_t(x,t) \quad (3)$$

$$F_s(t) = E_B S_B\, \varepsilon_t(x,t) \quad (4)$$

The strain rate $\dot{\varepsilon}$ is the ratio:

$$\dot{\varepsilon} = \frac{v_e(t) - v_s(t)}{\ell_0} \quad (5)$$

However, since the sample impedances (the mass density times the acoustic wave velocity in the material) are considerably lower than that of usual metallic bars, such classical bars cannot be used for this study as the impedance ratio would lead to a zero transmission coefficient and a reflection coefficient of 1. Then the reaction force at the input bar – sample interface would be zero, as if the interface was a free interface. For this reason, bars made of nylon were used in the present study. Due to the visco-elastic nature of this material the calculation needs to be adapted to rebuild the strain signal at the bar - sample interface using the strains measured at the remote gage locations. Gary et al. [18] proposed a visco-elastic correction based on the Pochammer-Chree model in infinite cylinders. The dispersion equation was solved by [19] and provides a correction that takes both dispersion and damping into account. The results presented below were processed with this visco-elastic/damping correction by a software implemented in the data acquisition system.

An example of the forces histories $F_e(t)$ and $F_s(t)$ is plotted in Fig. 1. The plot shows that an equilibrium state is reached only after a duration of 500 μs, corresponding to a round trip of the waves in the sample. By selecting appropriately the sample length ℓ_0, this duration as well as the strain rate $\dot{\varepsilon}$ may be adjusted. After this transient phase, the sample is in equilibrium ($F_e = F_s$) and the stress