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Development of numerical model for ballistic resistance evaluation of combat helmet and experimental validation

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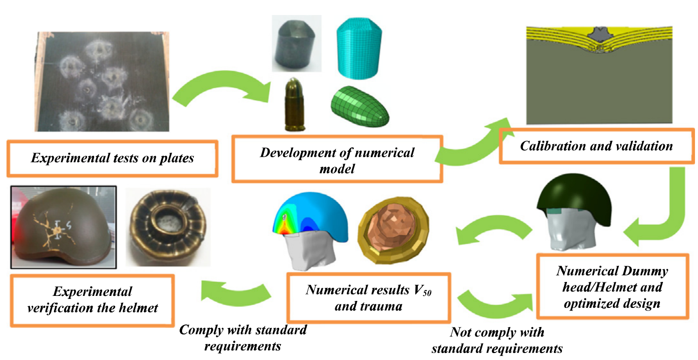
HIGHLIGHTS

- Numerical models of impact on aramid composite plates and combat helmet were developed.
- Experimental tests were carried out according to standards used by manufacturers.
- Good accuracy between predictions and experiments was observed proving the ability of the models developed as a design tool

GRAPHICAL ABSTRACT



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ABSTRACT

Modern designing process of combat helmets requires both numerical modeling and experimental validation in order to achieve exigent requirements combining impact resistance and reasonable weight. In this work a finite element model of a combat helmet is presented. Mechanical behaviour of the shell aramid composite under impact conditions was analyzed from experimental Fragment Simulating Projectile (FSP) and Full-Metal Jacketed (FMJ) impact tests on aramid flat plates. Numerical modeling based on finite elements method was used to simulate both impacts in simple plates of the composite and also the simulation of ballistic impact involving real ammunition and the complex geometry of the helmet including inner foam. Experimental work involving impact tests on composite plates and also ballistic test on the helmet with a dummy provided real data for comparison with models predictions and proved the accuracy of the numerical models developed.

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1. Introduction

Given the recent rise in terrorism, civil and international conflicts, the number of people afflicted with war-related Traumatic Brain Injuries (TBI) is increasing. In this sense, TBI is most often related to their exposure to blast and ballistic threats, such as those produced due to impact of shrapnel, shell fragments, and bullets.

In order to minimize the morbidity and mortality resulting from ballistic head injuries, that the role of personal protective equipment is crucial, especially in the case of the combat helmets. Modern designing process requires both numerical modeling and experimental validation

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Nomenclature

ACH	Advanced Combat Helmet
BABT	Behind Armor Blunt Trauma
BFD	back face deformation
BHBT	Behind Helmet Blunt Trauma
DIC	Digital Image Correlation
FE	finite element
FEA	Finite Element Analysis
FMJ	Full-Metal Jacketed
FSP	Fragment Simulating Projectile
ICP	Intracranial Pressure
NIJ	National Institute of Justice
PASGT	Personal Armor System for Ground Troops
STANAG	Standardization Agreement
TBI	Traumatic Brain Injuries

in order to achieve exigent requirements combining impact resistance and reasonable weight.

Designing of combat helmets have evolved considerably over the years from steel helmet at the beginning of 20th century to the helmet made of composite materials at the second part of 20th century, as Personal Armor System for Ground Troops (PASGT) or Advanced Combat Helmet (ACH) helmets [1].

Protective structures offering penetration resistance against incident high energy projectiles based on aramid composites have been commonly widely studied in the literature [2–6]. The most used aramid composite, Kevlar, presents excellent mechanical properties, mainly high strength, high modulus, and high strength-to-weight ratio.

The helmet's protective capabilities are commonly evaluated in terms of two parameters: the impact velocity (in general V_{50} velocity) and the back face deformation (BFD). The V_{50}, also known as the ballistic limit velocity, is defined as the required velocity of the projectile to perforate the target 50% of the times [12]. A minimum of two partial and two complete penetration velocities should be considered to determine the V_{50} velocity [7]. However, even when the helmet is able to stop the projectile, other serious injuries can occur such as Behind Helmet Blunt Trauma (BHBT). This trauma is caused due to no penetrating ballistic impacts since the energy deposited in the helmet by the retarded projectile may be transferred through the interior foams. BHBT is often associated with helmet back face deformation (BFD) [8].

The analysis of BFD requires a methodology to measure the trauma: a block of clay or gelatin is commonly used to get this goal. In some cases, a piece of clay is embedded in a ballistic dummy head. However, in the literature, it is also possible to found some experimental and numerical studies with a human skull [9–11] or numerical head models such as [12–15].

The experimental work of Sarron et al. [10] is one of the earliest papers focused on the analysis of BFD. The authors performed non-penetrating ballistic lateral impacts of a 9 mm projectile on silicone-filled dry skull protected by a polyethylene plate. This work has become a reference for further studies in the literature. Hisley et al. [16] quantified the helmet BFD and correlated it to BC injury. For this purpose, they used Digital Image Correlation (DIC) technique which allowed measuring dynamic displacements, for further calculation of deformation, velocity, and acceleration rates. Tham et al. [17] carried out experiments and simulations on the ballistic impact of a Kevlar helmet using spherical projectiles of 11.9 g at 205 m/s. Moreover, they developed numerical simulations with other type of projectiles; Full-Metal Jacketed (FMJ) 9 mm bullet at 358 m/s and Fragment Simulating Projectile (FPS); to obtain the V_{50} velocity. Tan et al. [18] carried out both experiments and numerical simulations of frontal and lateral ballistic impacts on a Hybrid III headform equipped with Advanced Combat Helmet (ACH) using 11.9 g spherical steel projectile at 220 m/s. Their analysis included quantitative parameters, such as head accelerations, helmet damage and deflection. Recently, Rafaels et al. [11] developed experimental analysis of seven postmortem human head/neck specimens wearing a ballistic protective helmet exposed to no perforating impact, using a FMJ 9 mm bullet with velocities of 400–460 m/s. They showed that the contact and fracture phenomena were generally different for Behind Armor Blunt Trauma (BABT) than those for direct penetrating trauma classically described in the literature.

Few experimental works have been published in the literature as it is shown in the aforementioned studies. The complexity of the experimental tests, involving expensive experimental devices such as ballistic gas gun, justifies the use of numerical models for simulation of BHBT.

In the early 2000s, Van Hoof et al. [19] performed ballistic impact tests on panels based on woven Kevlar composite using different types of projectiles. It was concluded that the relationship between the maximum backplane displacement and the impact energy is nearly linear within the range of impact energies considered in the work. Aare and Kleiven [20] determined numerically the effects of shell stiffness and impact angles on the level of the transferred load to the modeled human head. The main conclusion was that the helmet shell deflections should not exceed the initial gap between the helmet shell and the head in order to prevent the rear effect. The results were validated using the experimental data from shooting tests presented in [21].

In 2010, Lee et al. [22] developed numerical simulations in order to compare the protection efficiency of PASGT against head injury due to FSP and FMJ bullet when considering different interior cushioning systems. They concluded that the helmet together with its interior strap offered a good protection against small fragments but behaved poorer against large projectile rounds. Tan et al. [18] performed experimental ballistic tests and finite element (FE) simulations in ACH using spherical bullets in order to check the effectiveness of its interior cushioning systems. Another study of these authors, Tse et al. [12,23] developed a detailed numerical model of human head in order to obtain the Intracranial Pressure (ICP) in the brain and the maximum helmet deflection using FMJ bullet. A recent study was carried out by Li et al. [8]. They obtained numerically the BFD recorded by the clay using the dummy head/clay and by the helmet using FMJ bullet for different impact locations.

A summary of the main results obtained in the aforementioned works is summarized in Table 1 including projectile and protection type, velocity range and BFD obtained.

Innovative helmet designs require ballistic testing of the structural elements constituting the personal protection. Ballistic impact tests used by the manufacturers are defined in the standards NIJ Standard 0106.01 for ballistic helmets [24] and Standardization Agreement (STANAG) 2920: Ballistic Test Method for personal armor materials and combat clothing [25], being the most used by the manufacturers.

STANAG 2920 [25] uses chisel-nosed fragment-simulating projectiles (FSP) for proof-testing. The 1.1 g (17 grain) FSP with 0.22-caliber (5.5 mm diameter) is the most frequently used. This standard is used to calculate the V_{50} velocity of a specimen. In the simplest approach, V_{50} could be determined by averaging six projectile-striking velocities that include three lowest velocities that resulted in complete penetration and the three highest velocities that resulted in a partial penetration as it is explained in [17].

NIJ-STD-0106.01[10] establishes the performance requirements and methods of testing helmets intended to protect the wearer against gunfire. The standard classifies ballistic helmets into three types depending on the level of performance. This study focuses on Type II which states ballistic impact performance requirements for a helmet when impacted by 9 mm Full-Metal Jacketed (FMJ) bullet weighing 8 g (124 grain) from the front, side, rear and top of the combat helmet at 425 ± 15 m/s. A pad system and headform with ballistic clay Roma Plastilina No. 1 are used

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