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Modeling of impact dynamics and application in public security education

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Abstract

This work presents a methodology for interfacing with the students in order to study impact problems. The results are derived from the Bachelor Thesis developed at the end of the fourth course in the Security Engineering Degree. The knowledge regarding security topic and the use of new analysis tools (*commercial finite element solver*) have proved to be extremely useful for future Guardia Civil officers.

Keywords

Security Engineering Degree; impact; teaching methodologies; Bachelor Thesis

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1. Introduction

The threats to the public security and premises security are on rise because of increasing terrorism and violence. In this sense, the protection of civil infrastructures and critical industrial facilities are topics of increasing relevance to defence agencies and governments. Three key applications of armor systems may be considered in the security industry: (1) personal protection, including body armor and helmets, (2) vehicle armor, and (3) transparent armor. For each of these applications, specific requirements play an important role in the armor design and thus the ultimate choice of protection materials ensure that these systems are as lightweight as possible (Report, 2011a).

Impact dynamics is strongly related with physical security of persons and infrastructure. The analysis of impact processes is required for evaluation of threats, performance of protections and other important issues for law enforcement members.

The governing variables of the impact problem: target and projectile characteristics (geometrical and mechanical) and actual impact conditions (initial impact velocity).

The election of protective material is a key factor in armor design. For instance, the largest part of protection materials in the automotive sector is metallic, principally steel and aluminum alloys (Report, 2011a; Wilson et al., 1988). However, many hybrid systems are currently using in this field, which combine metals, polymers and plastics, with or without reinforcements (Mosse et al., 2006). On the other hand, the impact resistance of high-strength fabrics makes them desirable in applications such as protective clothing for military and law enforcement personnel. In this regard, aramid fibers as Kevlar (DuPont) and Twaron (Teijin) or ultra-heavy molecular weight polyethylene (UHMWPE), such as Spectra or Dyneema has been until now the most often used (Tabiei and Nilakantan, 2008).

The phenomenon of the process of perforation is often analyzed on terms of ballistic limit. The minimum velocity for a complete perforation of the target is called the ballistic

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limit V_b. At higher impact velocity ($V_0>V_b$), the velocity after perforation is called residual velocity V_r. The ballistic curve is described by initial impact velocity and residual impact which provides the essential information to enable the design of an efficient passive safety structure to resist an high velocity projectile of low mass penetrating a target.

Generally, the information of impact process is obtained by experimental tests; however; there are numerous parameters to analyze and consequently, an in-depth experimental study of the effect of each of these parameters would be extremely time consuming and expensive. The most common way to solve these inconveniences is to use numerical simulations because they provide a rapid and less expensive way to evaluate new design ideas. In the particular case of impact, it is easily possible to define a set of initial and boundary conditions.

The mechanical behavior of materials must be defined in order to simulate impact problems. In addition to defining an adequate finite element mesh, an important aspect of conducting successful penetration simulations is the use of adequate material failure models.

The knowledge about impact process, described previously, is key importance in the development of future Guardia Civil officers Learning. They could be drawn into such departments. For instance: Forensic science has needed to be adapted to new challenges in different areas in order to cover all aspects detected in crime scene such as understanding of projectile direction. Other example is traumatic injuries resulting from vehicular accidents or assaults; has been recently reported in the literature (Ni et al., 2013; Marco et al, 2015).

This work focuses on the Bachelor Thesis of students developed at the end of the fourth course in the Security Engineering Degree, trying to go further in the understanding related to security, different industries and scientific field using a finite element code.

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The next section shows a brief description about the relation between University Carlos III of Madrid and Guardia Civil University Centre.

The next sections show different Bachelor Thesis which were developed for students: the influence of shape projectile in the design of personal protection or the influence of layout of polycarbonate-aluminum in the design of crashworthiness structures, among others. These studies serve to link public, industrial and security interests and awake the interest and curiosity for research in the future Guardia Civil officers.

2. The institutions: Guardia Civil and University Carlos III.

The Guardia Civil is a Spanish national military law enforcement institution under the Home Affairs Ministry, focused on the protection of the free exercise of rights and freedoms and to ensure public safety. Since its foundation in 1844, it has been participating in the resolution of the main security issues affecting Spain as a State both nationally and internationally. Currently it is one of the most respected law enforcement agencies in the world owing strong international projection. The Institution is the final user of advanced technology for security.

The University Carlos III of Madrid (UC3M) was established by an Act of the Spanish Parliament on 5 May 1989, within the framework of the University Reform Act of 1983 (BOE nº108, 1989). From the outset it was intended to be a relatively small, innovative, public university, providing teaching of the highest quality and focused primarily on research. Both Engineering and Social Science studies are offered at this University.

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3. Methodology for interfacing with the students.

The students used knowledge learned in different subjects of the Security Engineering Degree. *Lightweight protection for mobile systems* and *Strength of Materials* are two subjects focus on impact mechanics. Students learn the principles of *Strength of Materials* such as stress, strain, inertial moment, yield stress, among others. In *Lightweight protection for mobile systems,* students acquire the basic knowledge for understanding the keys to design and analyse impact processes. Simple analytical and numerical models are explained. These approaches are developed for different materials and ranges of velocities according to needs of future Guardia Civil officers.

Once they have passed these subjects, students have a main idea in order to choose between different Bachelor Theses offered by experts in impact phenomenal of University Carlos III of Madrid.

The main drawback of development these Bachelor Theses is the interaction between students of Guardia Civil University Centre (GCUC) and experts of University Carlos III of Madrid (UC3M). The students, as future officers, have certain obligations subject to Guardia Civil institution. A methodology developed in order to solve these details as is shown in Figure 1.

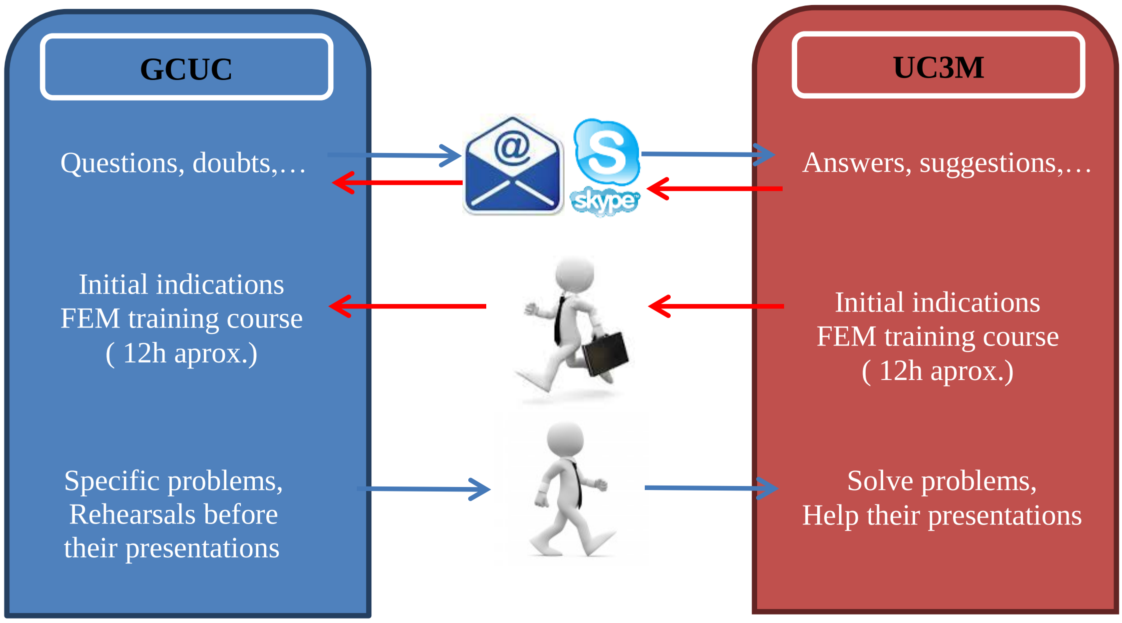

Figure 1. Schedule of interactions between Guardia Civil University Centre (GCUC) and experts of University Carlos III of Madrid (UC3M).

Three different ways have been thought to get a good interaction between students of GCUC and experts of UC3M: (1) emails and video conferences, (2) the experts visit Guardia Civil University Centre and (3) the students visit University Carlos III of Madrid.

Use of email and video-conference tools is most common method of communication due to its ease-of-use and quickly response. They usually use this method during the development of their Bachelor Theses. However, to hold a meeting of supervisor and students in the first steps of their Bachelor Theses development are needed. Students must understand the different parts of their study: aims, the significance of their work/research to GCUC, original contributions… Their supervisors help students to find these goals. In addition, an advanced knowledge to using commercial software of Finite Element Method (FEM) is needed in order to Bachelor Theses about impact problems get

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successful. For this reason, a FEM training course focusing on impact problems is developed for students and carried out in GCUC installations. It is conducted in 12 hours. After this course, students must work in their researches but they are always guided by their supervisors. However, the analysis of impact process is a complex problem when difficulties arise, it is necessary to organise a meeting. These meetings are usually in the installations of University Carlos III of Madrid. Finally, some examination drills are carried out in order to students gain self-confidence.

4. -The Bachelor Thesis and results

Given the recent rise in terrorism, civil and international conflicts, the number of people afflicted with war-related traumatic injuries is set to increase. The improvement of personal protections under ballistic and explosive threats is of great interest to Guardia Civil. Ergonomics, lightweight and security are the main requirements that personal protections must comply.

Figure 2 shows a schedule for design new armour/protections. Bachelor Theses are developed using numerical models due to the high required cost need for performing experimental tests. The numerical models are validated with data from literature. The layout work is similar to shown in Figure 2. Firstly, it is important to classify the type of protection: combat helmet, body protection, energy absorption structural element. The following is to choose material/s for the protection. Then, the development of numerical model which is adjusted to actual prototypes. Once numerical model is validated with data from literature, numerous analyses may be carried out in order to go further the knowledge for different frameworks: geometry of projectiles, incidence angle, initial impact velocities…

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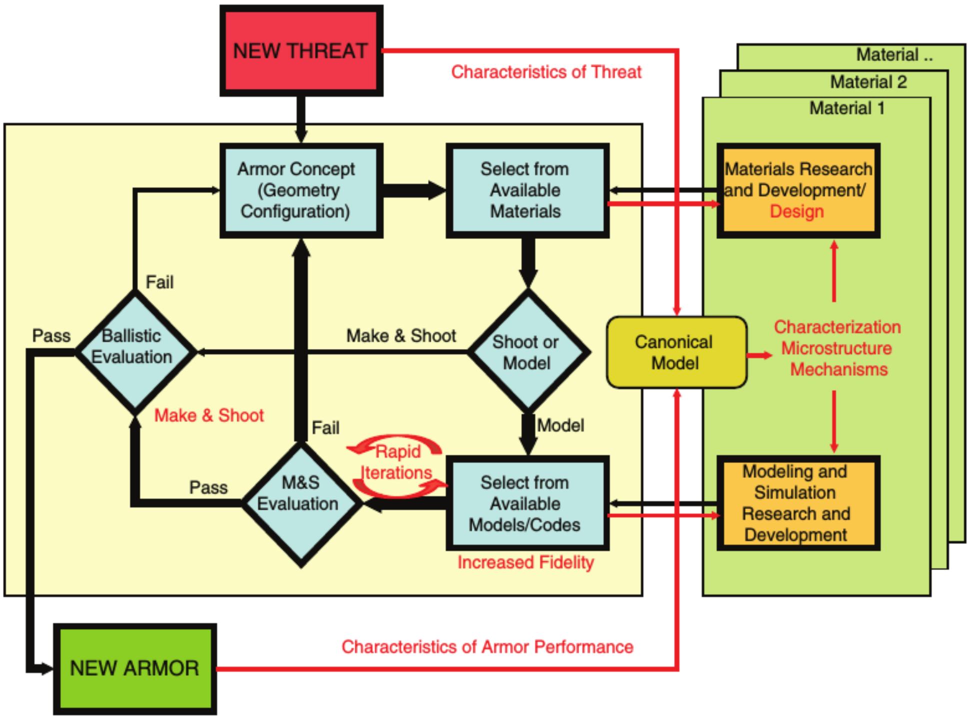

Figure 2. Schedule for armor development (Report, 2011b).

Different cases performed by the students of the CCUC developed during 2013/2014 are described below.

4.1: Numerical analysis of ballistic limit of Single and Layered Steel Plates.

Steels have been used widely used in armour designs for vehicles due to be less constrained in thickness. This allows using single and layered aluminium target plates with or without spacing, Figure 4. The idea of using layered plates instead of a single one in order to increase the ballistic perforation resistance is not new, and the effect of using targets made up of several thinner plates has been investigated in the literature for a long time (Corran et al., 1983; Britain, 1998; Dey et al., 2007; Deng et al., 2013).

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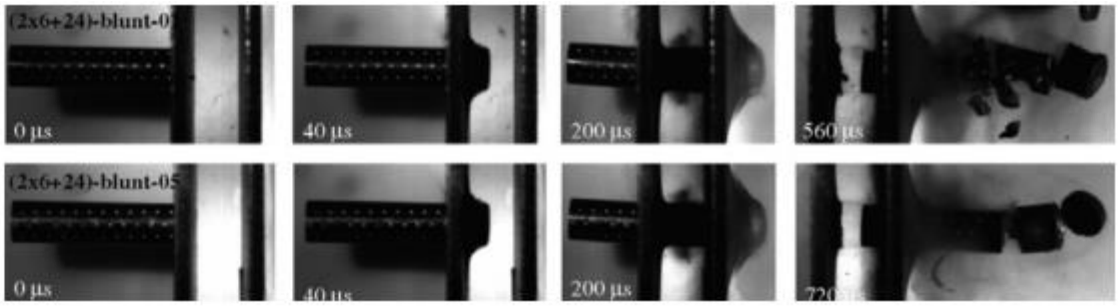

Figure 3. Example of perforation of separated thick target impacted by a blunt projectile. [11]

In this Bachelor Thesis, a numerical analysis of different parameters of impact problems was investigated: material behaviour, incidence's angle, thickness and air gap separation. ARMOX T500 and AISI 4340 were selected due to its different stiffness and they are widely used in the security industry. Both materials show a high strength, however ARMOX T500 shows low strain hardening and limited ductility. This fact is not clear in order to predict the ballistic behaviour on perforation plates (Rodríguez-Millán et al, 2014). The plates was impacted by using Ballistic Impacts of a Full-Metal Jacketed (FMJ) Bullet because it is currently one the most munition used for instance in "Kalashnikov AK-47".

ABAQUS/Explicit finite element code is used to simulate the perforation process. The thermoviscoplastic material behavior of the plates and FMJ bullet were defined using the Johnson-Cook model (Johnson and Cook, 1983).

The different studies carried out in this Bachelor Thesis are describing bellow.

i) Influence of material behaviour and thickness of plate on perpendicular impact test.

This analysis was carried out in order to find the ballistic limit varying the thickness of plates for an initial impact $V_0 \approx$ 750 m/s. AISI 4340 is a steel less strength than ARMOX 500T and this was reflected in Figure 4. The thickness required to prevent the perforation

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in AISI 4340 plate was more than three times than ARMOX 500T. The low strain hardening and limited ductility of ARMOX T500 may be the reason.

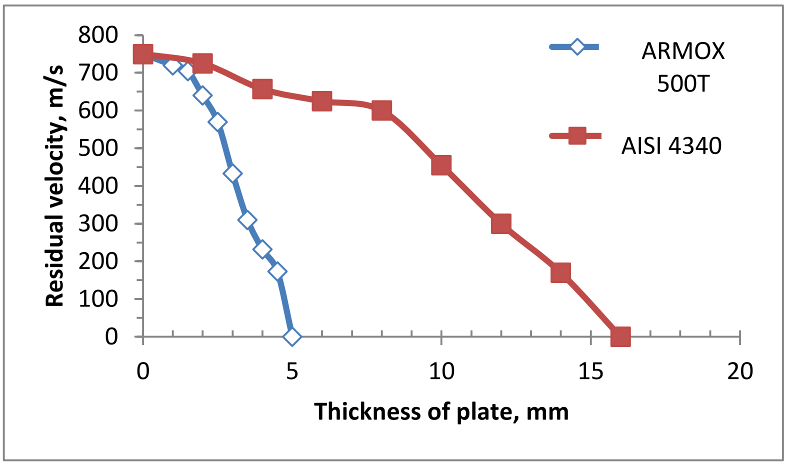

Figure 4. Residual velocity versus thickness of plate for ARMOX 500T and AISI 4340.

ii) Influence of angle of obliquity on impact tests.

The perforation resistance of armors impacted at certain obliquity is common described by the Equivalent Protection Factor (EPF), defined as the ratio of the areal density providing protection against oblique impact to the real density providing protection against normal impact. The EPF is commonly plotted against the angle of obliquity of attack as is shown in the Figure 5. This analysis revealed the reduction in armor thickness requires an increase in the incidence's angle of impact.

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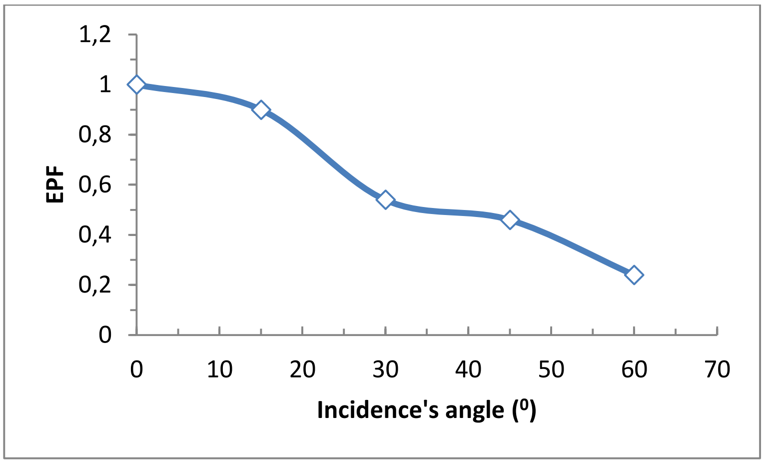

Figure 5. EPF versus obliquity impact for ARMOX 500T.

iii) Influence of layout in separated layered plates for a given initial impact velocity.

An analysis of layout of layered plates for ARMOX 500T and AISI 4340 was studied for normal and obliquity impact. The thicknesses were 4 mm and 3.2 mm for ARMOX 500T and AISI 4340 respectively. The air gap between both plates was 10 mm for two incidence angles (90^0 and 60^0) because this distance may be considered inside the vehicles. Figure 6 shows the final stage of the perforation process for the different cases studied. This study revealed that ARMOX-ASIS 4340 is the best layout configuration in terms energy absorption. Thus, the more ductile material (ASIS 4340) is better to place in the back of the layout in the design of absorption energy structures.

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a) b) c) d)

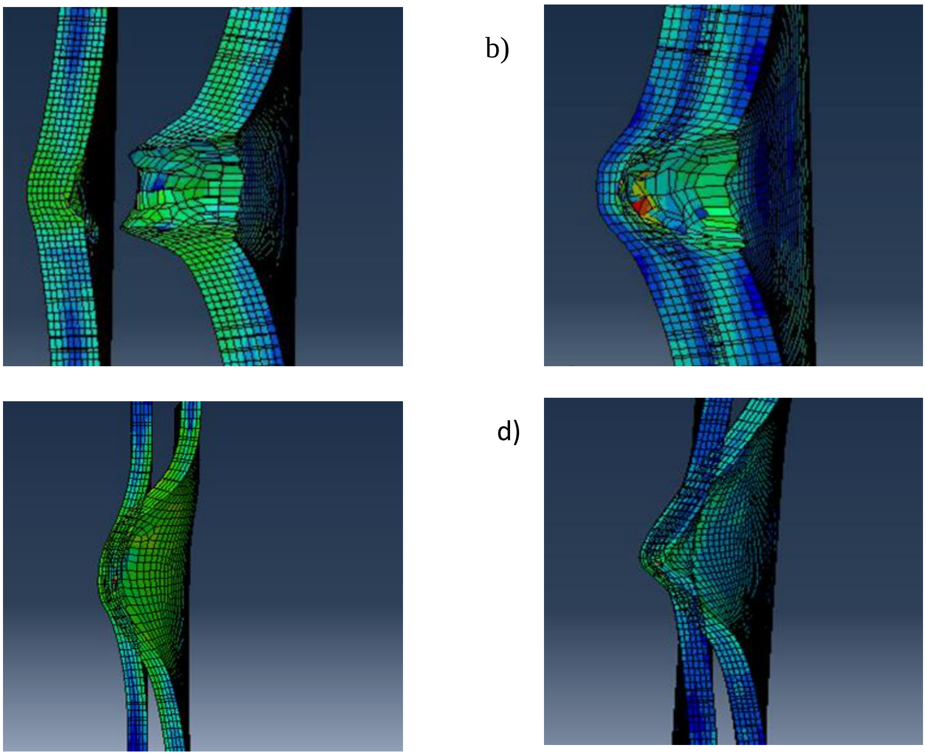

Figure 6. The final stage of the perforation process for: a) Normal impact and ARMOX 500T-AISI 4340 configuration of layout, b) Normal impact and AISI 4340-ARMOX 500T configuration c) Obliquity impact and ARMOX 500T-AISI 4340 configuration and d) Obliquity impact and AISI 4340-ARMOX 500T configuration.

4.2: Impact behaviour of welded metal shields: numerical study

Armour protection structures are susceptible to failures along welds and joints, and simulations of these events are not yet reliable. Although, this is a complex problem, a numerical analysis has been developed in this Bachelor Thesis in order to study the influence of obliquity in the impact process. The impact tests were analysed using the

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explicit solver of the finite element code ABAQUS. The target (AISI 4340) and FMJ bullet were modelled using the Johnson–Cook constitutive relation and fracture criterion.

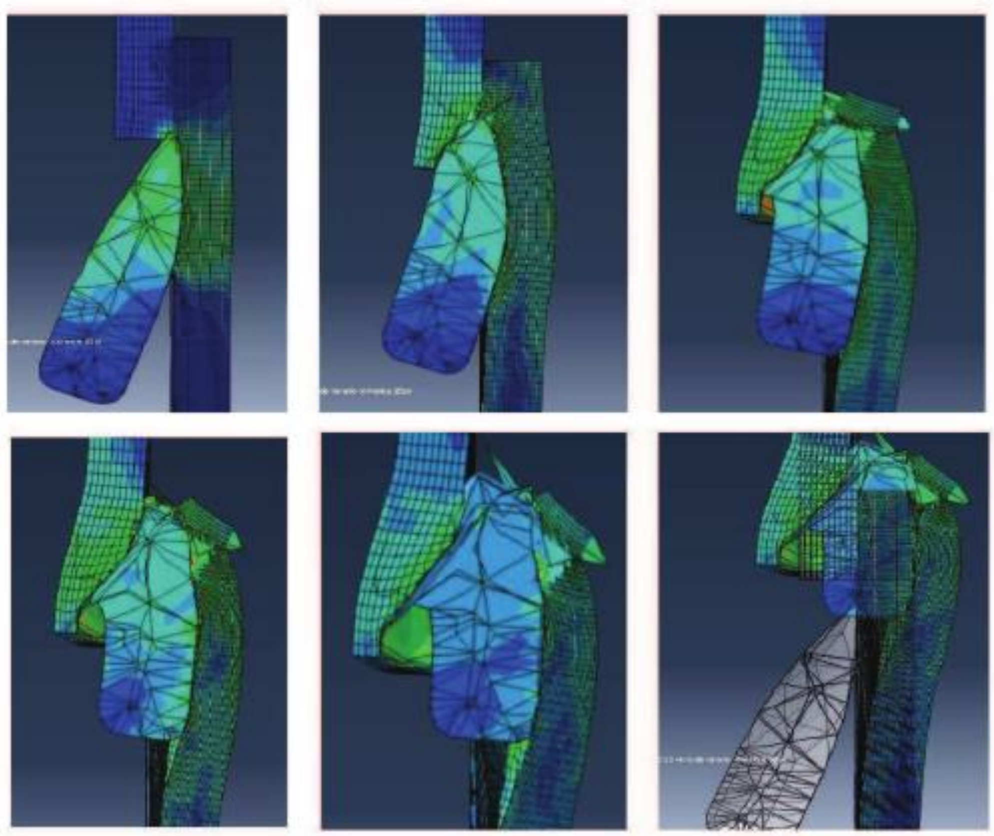

Figure 7. Example of impact process on welded plates.

Figure 7 shows a sequence of images during the impact process in the weld zone. Some of the most relevant results developed in the Bachelor Thesis are in Figure 8. The residual velocity decreases as incidence angle increased up to 60º. This fact is associated to an increase of effective thickness which is varied with incidence angle. However, Ricochet phenomenon is revealed beyond 60º, in other words, the interaction between projectile and surface is lower and therefore, the projectile does not get perforate the plate.

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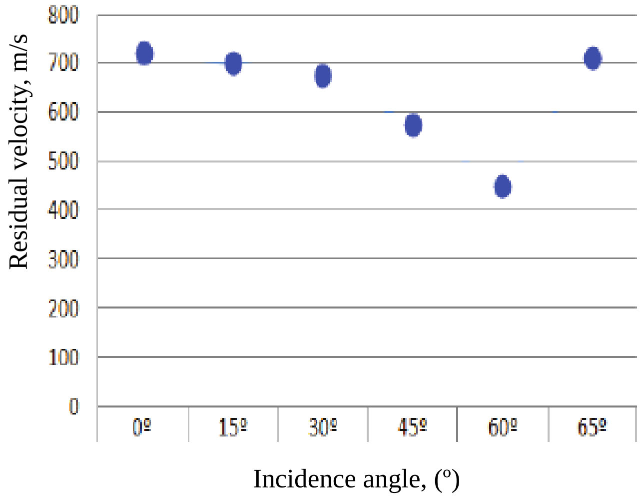

Figure 7. Residual velocity versus incidence angle on welded plates.

4.3: Numerical investigation on the impact behaviour of multi-layered composite plates of polycarbonate and aluminium.

In this Bachelor Thesis, a numerical model is developed in order to study the influence of layout in multi-layered composite under impact loading. Sandwich material systems – as special hybrid materials- are made by plates of polycarbonate and aluminium. They can combine the advantages of miscellaneous materials (e.g. low density, high bending resistance, energy absorption, high load-capacity at low weight) with each other (Librescu and Hause, 2000). Three-layered example of metal/polymer/metal sandwich systems is HYLITE (Carradò et al., 2011). HYLITE is an aluminium/polypropylene/aluminium SMS with thicknesses 0.2/0.8/0.2 mm which was introduced into the automotive market through the Audi A2 as is shown in the Figure 8.

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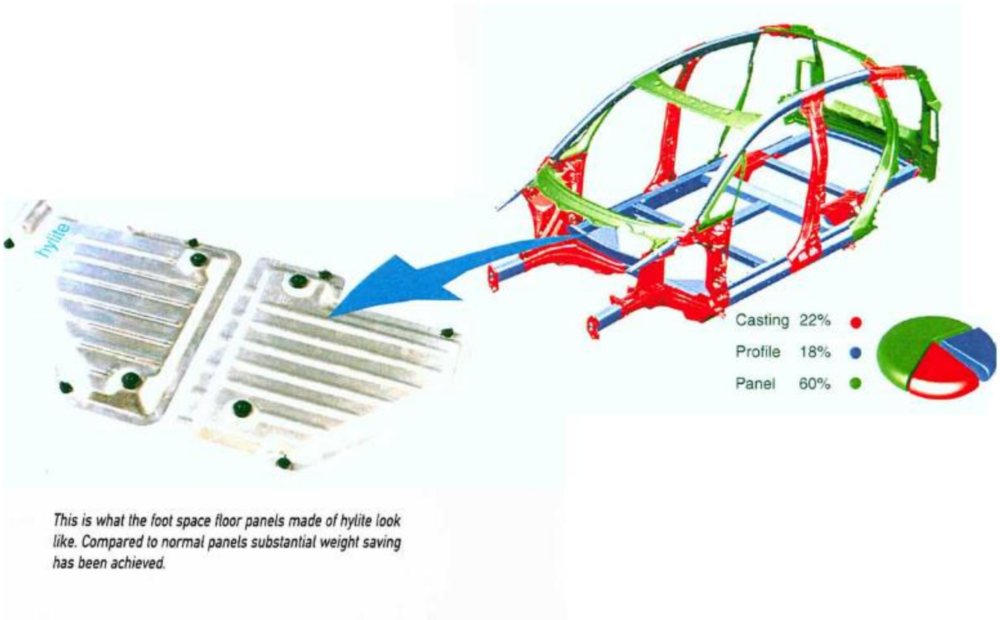

Figure 8. Location of sandwich material systems (HYLITE) in Audi A2 (Display.3acomposites, 2015)

Six different layout of Polycarbonate (PC)-Aluminum Alloy (AA) plates were analysed: (i) PC-AA-PC-AA, (ii) PC-AA-AA-PC, (iii) PC-PC-AA-AA, (iv) AA-AA-PC-PC, (v) AA-PC-AA-PC and (vi) AA-PC-PC-AA. ABAQUS/Explicit finite element code is used to simulate the perforation process. The thermoviscoplastic material behavior of the plates was defined using the Johnson-Cook model (Johnson and Cook, 1983). The projectile is defined by an analytical rigid body since experimental tests revealed no plastic deformation on the projectile-surface after impact. This definition allows reducing the computational time required for the simulations.

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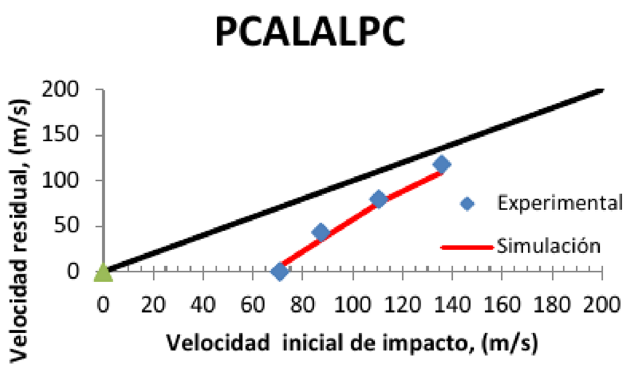

Figure 9. Comparison between experimental test and numerical model in terms of residual velocity-initial impact velocity.

The numerical simulations were compared to experimental data developed by UC3M as is shown in the Figures 9-10. Figure 9 shows a comparison between numerical results and experiments in terms of ballistic curve V_R –V_0. A good agreement is observed between numerical simulations and experiments. In addition to the ballistic curve, local deformation was estimated, Figure 10. Petalling mechanism was revealed for all plates.

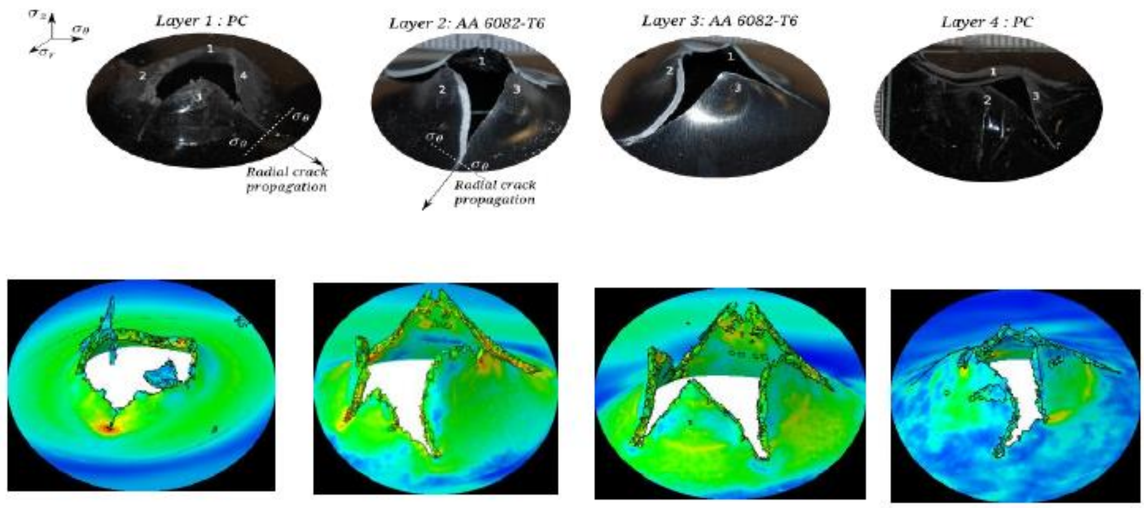

Figure 10. Comparison of final stage of the perforation process for the PC-AA-AA-PC configuration between experimental tests and numerical simulations.

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From analysis developed in this Bachelor Thesis some conclusions are revealed. AA-PC-PC-AA is the best layout configuration in terms energy absorption. Thus, the more ductile material (PC) is better to place in the middle of the layout in the design of absorption energy structures. Johnson-Cook model has proved insufficient in order to simulate the thermoviscoplastic behaviour of polycarbonate plate.

4.4: Numerical study of different aramid fibers under normal impact process.

Composites have become increasingly important in defence and security industries in the last years. The use of these materials in combat helmets, body protections and combat vehicles requires an exhaustive analysis of their behaviour in order to satisfy the safety requirements. One of the main challenges of modern personal protection is the optimization for energy absorption. In this sense, personal protections are usually based on fibre reinforced polymer composites, especially Kevlar and Twaron fibres due to its high stiffness, light weight and high energy absorption capacity.

In this Bachelor Thesis, a comparison between different aramid fibers was developed using ABAQUS/Explicit finite element code to simulate the normal perforation process. The modelling of composite material in a code of finite element is hard task. However, possible simplifications of mechanical behaviour of composites may be carried out by the development of shell models. The parameters for modelling of aramid fibers were found in the literature (Gower et al., 2008; Talebi et al, 2009).

Figure 11 shows the residual velocity versus initial impact velocity for three different aramid fibers: Kevlar 29, Kevlar 129 and Twaron. This study revealed that Twaron has more energy absorption capacity for the used boundary conditions.

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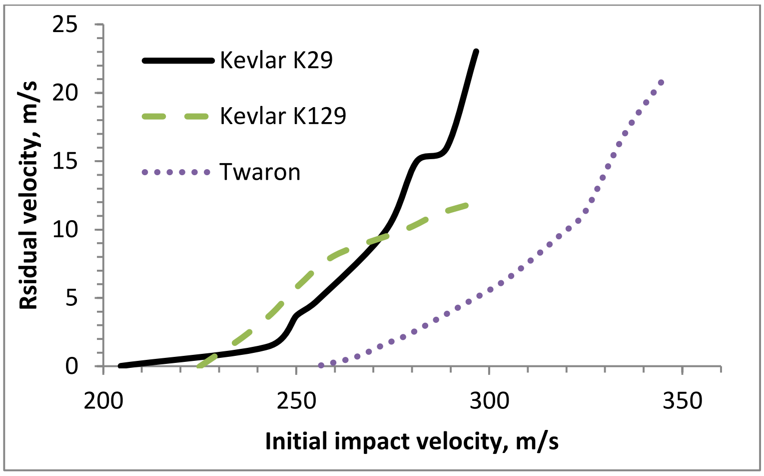

Figure 10. Residual velocity versus initial impact velocity for three different aramid fibers.

5. Conclusions

The experience of development of Bachelor Thesis structure, evaluation and topics has constituted a challenge for both institutions Guardia Civil and University Carlos III of Madrid.

The perception of students and advisors has been highly positive. Students have the opportunity to develop real applications of the knowledge and abilities acquired during their degree. The contact with operative units of Guardia Civil seems crucial to achieve this objective, proposing to impulse some specific topics to be rapidly adapted in their units.

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