Numerical recreation of Police Field Cases on a human body FE model: first insights into BABT

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Abstract Behind Armor Blunt Trauma (BABT) has become a topic of main importance for the law enforcement officers, soldiers and armour manufacturers. Indeed, the need for body armour weight reduction and the enhancement of projectile efficiency may result in a higher body armour deformation and therefore, an increasing risk of blunt trauma. This study focuses on the soft body armour deformation where trauma is mainly induced by the dynamic deformation of the protective system. Indeed, for the velocity range considered, it is assumed that trauma linked to shock waves may be neglected.

Three US Police field cases intend to be numerically investigated through impact simulations on a biofidelic human torso Finite Element (FE) model. These cases involve a wide range of BABT, from bruising to rib fractures and lung contusion. In order to faithfully replicate impact conditions on a human body FE model, a previously published method is used to propose a FE modelling of projectiles and body armours. It basically relies on impact events recreated on a transparent synthetic SEBS gel and dynamic gel wall displacement profile measurements.

Firstly, projectiles and protective systems are modelled through an inverse iterative approach using both experimental and numerical model of the gel block. The maximum backface deflection is used as objectives to reach in the identification procedure, along with the shape of the deformation. Secondly, impact conditions related to each field case are replicated on the torso FE model. Following observed trauma, strain, pressure fields and derived metrics are computed from the human body model. Then, comparisons of trauma and numerical metrics values are made and first conclusions are drawn. This study represents an important step along the way to a better understanding of BABT and human body-protective systems' interactions.

1. INTRODUCTION

Ballistic protective systems are in constant improvement to absorb the kinetic energy of projectiles and prevent penetration. The requirement of body armour weight reduction may cause a higher deflection of armours covering the body and consequently an increasing risk of Behind Armour Blunt Trauma (BABT) [1, 2]. Over the last decades, numerous experimental methods have been established to assess body armours. For example, it led to the well-known National Institute of Justice (NIJ) Standard-0101.06, where Roma Plastilina No 1 clay is used as target material placed behind the studied body armour [3]. Among others ballistic testing media present in the literature, the polymer SEBS (Styrene-Ethylene-Butylene-Styrene) gel exhibits advantageous properties: transparency, mechanical consistency and environmental stability [4-7]. This material is adopted in the present study to analyse non-penetrating ballistic impacts.

The use of Finite Element (FE) modelling is also considered in order to replicate impact conditions on a biofidelic human torso model. The Hermaphrodite Universal Biomechanical YX model (HUByx) is a commercially available human body model in Altair HyperWorks software packages developed by CEDREM. This model has been validated against ballistic impact replications and respective biomechanical corridors [8, 9]. Nonetheless, several papers point out the complexity of numerical modelling of ballistic impacts involving body armours [10-13]. A solution is proposed by

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Bracq et al. [14]. It is based on an equivalent modelling of projectiles and body armours. The approach mainly relies on experimental and numerical modelling of ballistic impacts on a SEBS gel block [14].

However, results of ballistic impact simulation are meaningless without comparisons with actual field cases. A recent research work of Bir et al. reports 47 police field cases while providing useful information as body armour properties, fired ammunition and sustained injury [15].

The aim of the present paper is thus to recreate numerically some of the most relevant field cases mentioned in the study of Bir et al. [15] and correlate numerical metrics with observed injuries. For this purpose, the authors depict chosen police field cases and present the coupled experimental-numerical method to complete a FE model of the incident. Then, experimental and numerical results are provided and discussed. Finally, conclusions are drawn about the potential of FE modelling but also the requirement of statistical data. This may bring other perspectives to current standards for body armour assessment.

2. MATERIAL AND METHODS

2.1. Description of police field cases

Three police field cases are available in the present study and their data originate from the study of Bir et al. [15]. They are the main results of continuous efforts made by the IACP/DUPONT® and Safariland members to assess protective systems and potential BABT. Police officers' testimony, medical and police records as well as information regarding the manufacturer, model and threat level of the ballistic pack worn during the incident were collected. The injuries observed were classified following two injury scales. The first one noted IR and introduced by Bir et al. [15] ranks injuries from 1 to 3 according to clinical significance:
1 = minor - bruise, red mark, minor wound care for abrasions
2 = moderate - bruising with penetration (BFS), lung contusion, open wound care
3 = severe - internal injuries requiring medical intervention, advanced wound care
The Abbreviated Injury Scale (AIS) is also used to rank injuries while taking into account trauma location on the body. Table 1 outlines the collected data for every field case.

Table 1. Summary of field cases data used in this study [1].

Case	Armour	Projectile	Range [m]	Impact location	IR	AIS	Injury details
USC-990	Second Chance Ultima SMU II, Level II	Remington 40 Cal S &W 180 gr	2.4	Left flank at level of 8^{th} rib	3	2	Broken 8^{th} rib, contusion/ laceration of spleen, hemo peritoneum
USC-1716	PACA KSG, Level IIIA	RWS 38 special 158 gr FMJ	0.9	Upper right corner, just above trauma pack	1	1	Skin contusion
USC-3138	Point blank, CIIA-1 Level IIA	Federal Premium 40 cal, S&W, 180 gr HP	<0.3	Front upper torso, right of center	2	3	Pulmonary contusion

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2.2. Experimental-numerical method for impact FE modelling

In order to carry out impact modelling on HUByx and evaluate BABT, projectiles and body armours need to be modelled. The complexity in such modelling forced the authors to propose a methodology based on experimental and numerical approaches. Firstly, it relies on experimental tests on a gel block. This procedure has already been fully depicted in a previous paper [14]. Thus, only the most relevant part will be presented here.

The ballistic testing media is the polymer gel SEBS. A gel sample is created by mixing SEBS powder and mineral oil with a SEBS/oil ratio about 30/70%. Firearm projectiles are impacted on the centre of body armours using a 25 cm gel block cube as backing material. A barrel is employed to fire any projectiles. Hook and loop straps are employed to hold still body armours against the gel block surface as shown in Figure 1 (right). Moreover, the gel transparency leads to the measurement of the dynamic gel wall displacement due to armour deformation through the use of a lighting system and a high-speed camera. Images are processed to capture the gel wall displacement history using gray level thresholding. The experimental set-up dedicated to non-penetrating impacts is illustrated by Figure 1 (left). Other metrics can be deduced from gel wall displacement curves. A pseudo viscous criterion defined in the literature may be calculated from the gel wall displacement (Xmax) [16]. It is called Energy Transfer Parameter (ETP), expressed in m/s. The displaced volume (VOL) may also be computed at each time and its derivative, the volume growth rate (VGR). The maximum value of each parameter can be employed to analyse experiments.

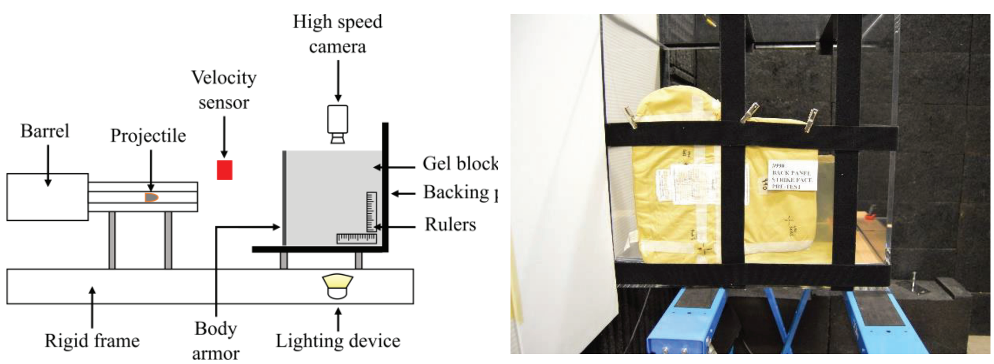

Figure 1. Experimental set-up for ballistic impact studues (left) and body armour positioning before ballistic experiments (right).

The gel wall displacement profile captures the projectile kinetic energy dissipated by both the gel block and the body armour. Therefore, the mechanical properties of the body armour can be determined if the SEBS gel material behaviour is known. Actually, a visco-hyperelastic model has been implemented for the constitutive modelling of the SEBS gel [4, 17]. An inverse methodology can be applied by modelling impact experiments on the gel block and optimizing model parameters to fit with experimental data. However, the impact modelling of a projectile on a body armour still results in complex phenomena and high computing costs.

Hence, the authors developed an equivalent FE modelling of the impact based on several assumptions. These assumptions rely upon the physical phenomena occurring before the gel wall displacement [14]. Thus, the projectile is considered as rigid in the equivalent FE model and its novel geometry is identified through the analysis of the gel wall displacement profile during an impact as well as the measurements of the actual projectile geometry after impact. By means of the length of the real deformed projectile, the equivalent rigid projectile can be meshed using the commercial software HyperMesh (Altair HyperWorks ©). The material density indicated for simulation is adjusted to obtain an equivalent mass with the actual projectile. Then the body armour is modelled at the macroscopic scale with one layer of 2D shell elements, as illustrated in Figure 2 (right). It simplifies the modelling and reduces computing costs. A simple anisotropic hyperelastic law for fabric material proposed by the

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explicit code Radioss (LAW58) is used for the constitutive modelling of body armours. When the impact is located far from the edges of the ballistic pack, planes of symmetry are employed for impact modelling reducing the FE model to a quarter (Figure 2 (right)). Such boundary conditions can be imposed because gel block dimensions and impact location make it possible to neglect edge effects.

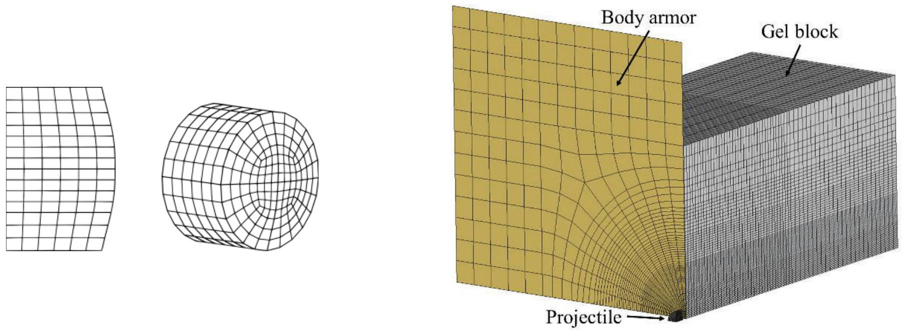

Figure 2. FE modelling of an equivalent projectile (left) and representation of the FE model developed to simulate ballistic impacts on a gel block.

An optimization procedure is carried out to identify model parameters to fit with experimental gel wall displacements and their 2D profiles. Relevant model parameters include the projectile initial velocity, the density of the body armour, its thickness and its shear modulus. Finally, a Response Surface Method proposed by the software HyperStudy is chosen to optimized parameters. Once the model parameters adjusted for each impact condition, experimental and numerical results can be compared. For instance, this procedure is applied to an impact of a 9 mm bullet on a soft body armour made of 40 layers of para-aramid Kevlar® fibres protecting a gel block. Figure 3 (left) presents the experimental and numerical profile at maximum gel wall displacement. Figure 3 (right) illustrates experimental and numerical gel wall displacements over time.

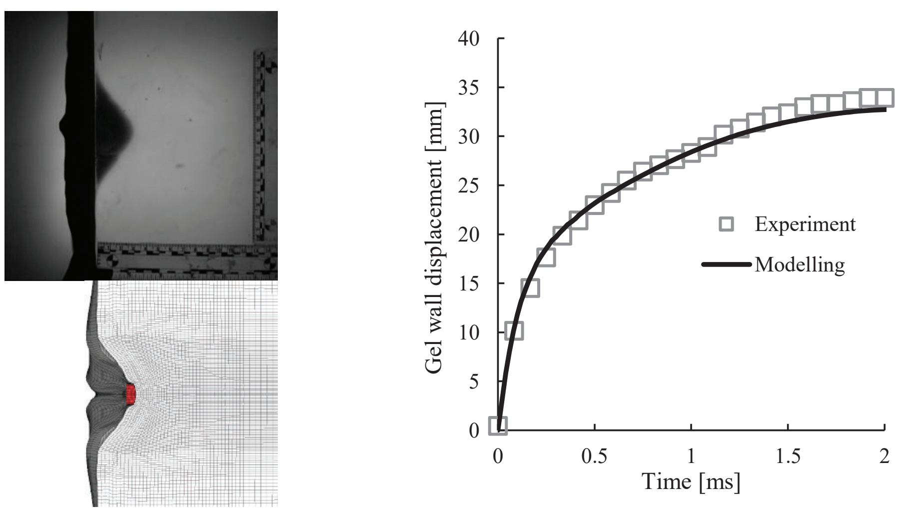

Figure 3. Experimental and numerical profile at maximum gel wall displacement (left) and experimental and numerical gel wall displacements versus time (right).

2.3. Human torso Finite Element model HUByx

The FE model HUByx is developed by means of a 3D reconstruction of the human torso geometry and corresponding CT scans image processing. A 50th percentile male subject has been created. Through the

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HyperMesh software (Altair HyperWorks ©), a finite element model is constructed with skin and muscle, skeleton and internal organs [8, 9]. A detailed description of this FE model in terms of mesh discretization, contact interfaces and material models depicting the human body response under complex and dynamic loadings can be found through the article of Roth et al. [9]. However, this study focuses on behind armour blunt trauma such as rib fractures and lung contusion.

Once the hybrid method presented in the latter part is applied to the studied case, impact conditions can be simulated on HUByx at a considered location. Figure 4 intends to illustrate the FE model of the projectile, the body armour and HUByx. Mesh discretization procedure to model the projectile and the body armour is preserved from the identification process.

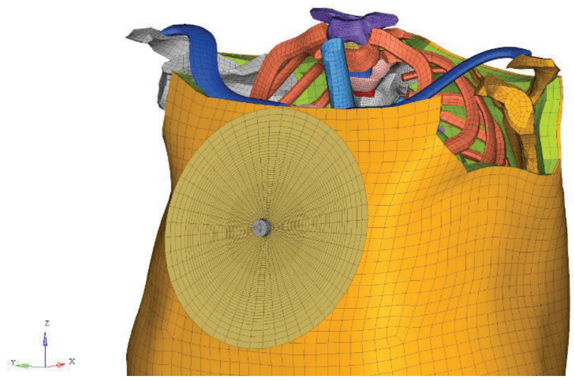

Figure 4. Representation of a FE impact modelling on HUByx [14].

To relate numerical simulations with the appearance of blunt trauma requires first of all a procedure to compute relevant numerical metrics. As suggested by the authors in a previous study [18], numerical pressure fields of the 3D elements depicting soft tissues are processed. The following softwares HyperView, HyperGraph and MatLab are combined to identify the maximum pressure over time for the body part of interest. Additional numerical metrics can be deduced from pressure time history as the pressure impulse, the peak of pressure, the duration of the pressure wave above 75% of the pressure maximum value as well as the wave duration. The risk of rib fractures is numerically accounted for by computing the maximum value of the specific energy field of the rib cortical bone. A simple average filtering method is proposed in HyperView and used to record numerical values. The following part of this paper will focus on the recreation of some Police field cases and first outcomes regarding BABT and their mitigation.

3. RESULTS AND DISCUSSION

3.1. Ballistic experiments on synthetic gel

Based on the case reports, impact conditions were faithfully reproduced on exemplar body armours. Stand-off distance, ammunition and impact location were carefully chosen. One ballistic experiment is carried out for each case. Images from the high-speed camera Phantom V1212 are saved at 20,000 frames per second with a resolution of 640x480 pixels. The image and data processing routine is used to determine the 2D gel wall displacement profile at each time step. Figure 5 to Figure 7 present a high-speed image at maximum gel wall displacement and the dynamic contour profile for each case.

Post impact projectiles' dimensions are measured such as the maximum diameter D and the thickness or width e. Table 2 summarises the impact conditions, "post-mortem" projectile dimensions and geometry for various case studies. Experimental metrics are also derived according to the gel wall deformation, as for instance the maximum gel wall displacement Xmax or the maximum displaced volume VOL (Table 3). These data added to 2D dynamic contour profiles are mandatory to apply the modelling procedure and to propose suitable ballistic simulations.

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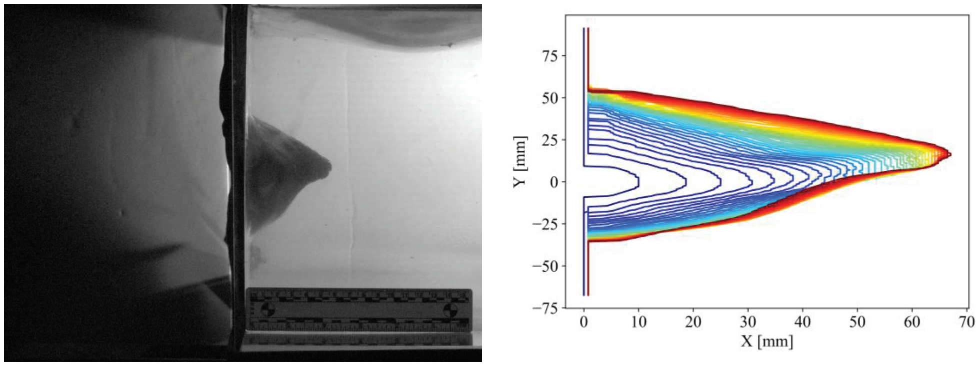

Figure 5. High-speed image at maximum gel wall displacement (left) and 2D dynamic gel wall displacement profile (right) related to the field case USC-990.

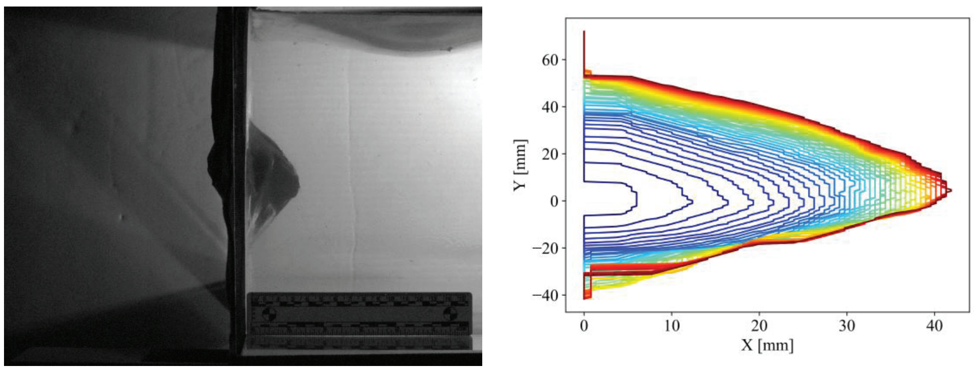

Figure 6. High-speed image at maximum gel wall displacement (left) and 2D dynamic gel wall displacement profile (right) related to the field case USC-1716.

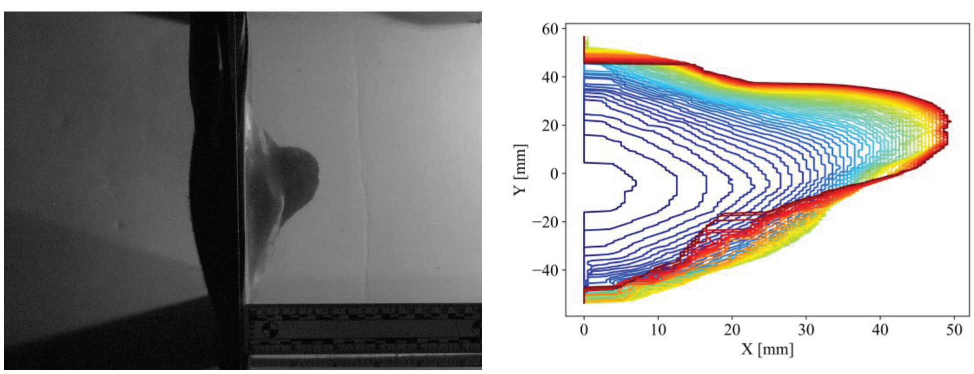

Figure 7. High-speed image at maximum gel wall displacement (left) and 2D dynamic gel wall displacement profile (right) related to the field case USC-3138.

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Table 2. Projectile characteristics, from impact condition to post impact figures, for three field cases.

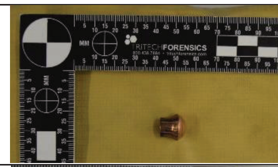
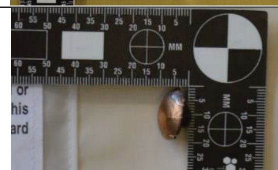
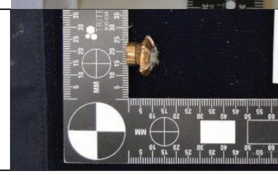
Case field	Projectile	Mass [g]	Velocity [m/s]	Post impact photograph	D [mm]	e [mm]
USC-990	.40 S&W 180 gr FAE FMJ	11.67	295.4		13.3	12.9
USC-1716	.38 158 gr FMJ FN GECO	10.20	262.2		17.6	10.0
USC-3138	.40 S&W 180 gr FP JHP	11.71	297.3		11.0	11.6

Table 3. Experimental metrics related to ballistic tests on SEBS gel block for three Police field cases.

Case field	Xmax [mm]	t_{Xmax} [ms]	ETP [m/s]	VOL [cm^3]	VGR [dm^3/s]
USC-990	67.1	2.2	15.4	185.5	168.5
USC-1716	41.9	2.1	6.3	112	102.2
USC-3138	49.6	2.9	6.5	199.5	179.1

3.2. FE modelling of impacts on synthetic gel

Numerical simulations of impacts on the gel block are firstly performed. The objective is the identification of the parameters, by an optimisation procedure, of an equivalent model of the body armour as well as the initial velocity. The boundary conditions were faithfully reproduced as experiments like presented in the previous section (2.2). Impact locations close to the body armour's edges prevent from using planes of symmetry. The equivalent projectiles forms identified from the analysis of the gel wall displacement are modelled as presented in Figure 8.

Figure 8. Equivalent projectile geometry for three field cases.

Results obtained for the three cases are presented in terms of gel wall displacement over time (Figure 9) and all the parameters are given in Table 6. A good correlation is observed for all cases. Nevertheless, some discrepancies are present for the USC-990 case due to a large wall displacement, which leads to some mesh distortion at the end of the numerical calculation.

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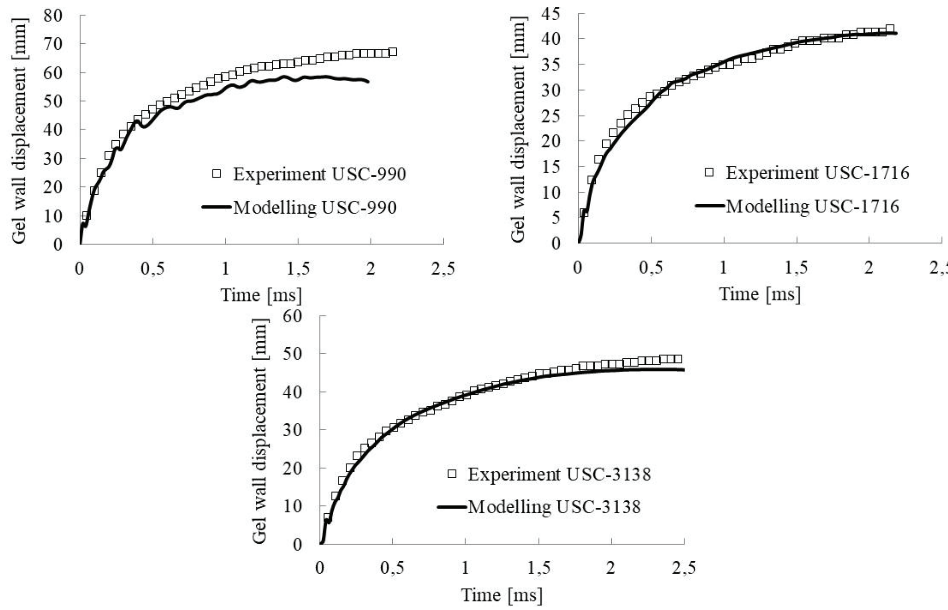

Figure 9. Numerical and experimental comparison of the gel wall displacement for three field cases.

Table 4. Optimized parameters of the projectiles / body armours equivalents models for studied cases.

	Body armour			Projectile
Case field	**Density [kg/m^3]**	**Shear modulus [MPa]**	**Thickness [mm]**	**Velocity [m/s]**
USC-990	1.46×10^3	0.101	2.173	241.5
USC-1716	1.16×10^3	0.101	2.710	175.7
USC-3138	2.34×10^3	0.098	1.645	154.4

Field cases are then numerically reproduced with the HUByx dummy and the equivalent body armour. Locations of bullet impacts are proposed according the documents produced from the study of Bir et al. [15] and highlighted by a red circle on Figure 10. Numerical data are collected, especially the specific energy on the ribs and the lungs peak pressure.

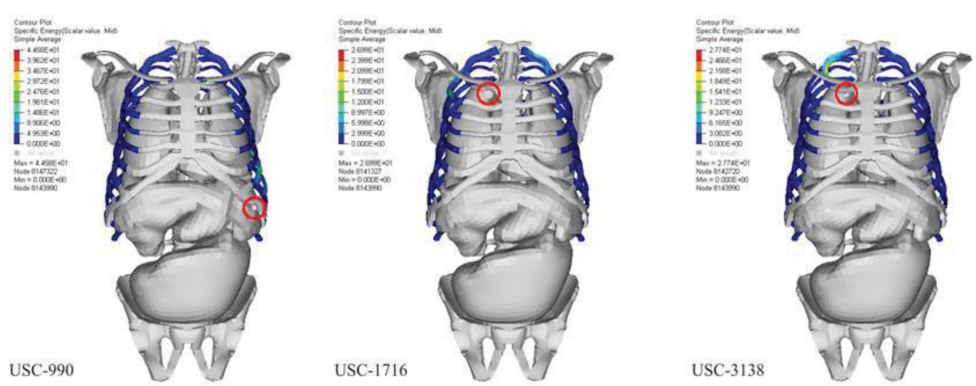

Figure 10. Specific energy fields of the ribs cortical bone for the three field cases.

A high specific energy is obtained on 8th rib for the USC-990 case and lower but similar ones for the other two cases. Concerning the pressure, the lungs are not loaded during the impact for the USC-990 case which is indicated by N.A. in the Table 5. For the USC-3138 case the maximum pressure value is higher with a shorter duration compare to the USC-1716 case. Pressure values are numerical data and probably not representative of the real ones in the human body.

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Table 5. Results of impacts on human body FE model for three field cases.

	Ribs Specific Energy	Lungs peak pressure		
Case field	Max value [J/Kg]	Maximun [MPa]	Duration [ms]	Integral [MPa.ms]
USC-990	44.58 (8th Rib)	N.A.	N.A.	N.A.
USC-1716	26.99 (2nd Rib)	0.8897	0.8897	0.3856
USC-3138	27.74 (1st Rib)	0.9806	0.5660	0.4644

Such data lead the authors to investigate correlations with BABT. Data obtained from the HUByx simulations, in terms of ribs specific energy, could be added to the injury risk curve already created with data from 22 cases based on various projectiles, armours and impact speeds [19]. This curve gives the probability to have a rib fracture with a corresponding AIS score between 2 and 3.

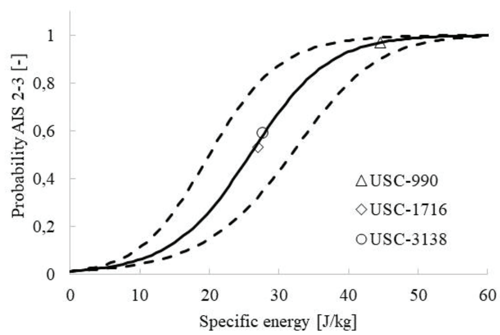

Figure 11. Injury risk curve with 95% confidence interval and injury prediction for three field cases.

The risk of rib fractures is about 97% for the USC-990, in agreement with the field case. Moreover, the same rib is broken in the simulation and in the field case. For the two other cases, the probability of rib fractures is close and about 53% and 58% for USC-1716 and USC-3138 respectively. No rib fracture is observed for these latter. For the USC-1716, the anthropometric values (1.80 m height and 88 kg weight) are higher than the 50th percentile representation of the virtual HUByx dummy. Therefore, the rib fractures probability obtained by this simulation is certainly overestimated. Unfortunately, for the USC-3138 case the anthropometric values are not given in the field case report. About the numerical pressure analysis, no data is available in the literature and thus, the probability to sustain a lung injury can't be determined. However, with these field cases, a lung injury is observed for the USC-3138 and none for the USC-1716. Data available in Table 5 don't yet enable the authors to conclude over the lung risk injury best indicator. More field cases are necessary to proceed further with this investigation.

4. CONCLUSION

The present paper intends to draw a combined experimental-numerical approach to assess the risk of behind armour blunt trauma. To obtain a representative study the authors have been encouraged to rely on police field cases available in the literature. Three relevant cases have first been recreated on a SEBS transparent gel block placed behind exemplar body armours and targeted by appropriate ammunitions. Image processing routine has provided precious measurements of the dynamic backface deformation of the ballistic pack. The experimental metrics are employed to propose a numerical modelling of the impact. Basically, an equivalent projectile/body armour FE model is identified through direct and indirect identification techniques. The objection function to minimize in the inverse iterative approach is a function of data from ballistic tests on a gel block and their numerical simulations. Comparisons of experimental and numerical gel wall displacements for recreated police field case validate the methodology. Then, impact conditions are modelled on the human FE model HUByx as reported in field cases. The simulation results as specific energy values correlate with a risk curve of rib fractures

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according to anthropometric data and impact locations. Numerical pressure values of the impacted lung are computed and can be related to lung contusions. However, the lack of datasets prevents the authors from establishing a risk of injury curve. Law enforcement agencies and industries have to make an effort to share statistical data for further investigations in BABT.

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