Numerical Methods for the Analysis of Behind Armor Ballistic Trauma

Pawel Zochowski[1]

[1]Military Institute of Armament Technology, 7 Wyszynskiego str, 05-220 Zielonka, Poland

1 Introduction

The asymmetric character of current military conflicts causes that soldiers are often exposed to projectile impacts. Body armor (helmets, vests, etc.) protects them from the negative effects of highly dynamic loads by absorbing and dissipating kinetic energy of a projectile. However, severe local and distant injuries can occur in the human body, even in case of a non-perforating impact. A large amount of energy and momentum is converted into deep back face deformation (BFD) of the armor and dynamic acceleration of the body walls. In case of high-velocity impacts a trauma may be caused also by the stress waves generated and propagated through the tissues. Injury of the human body as a result of non-perforating projectile impact into the armor is defined as Behind Armor Blunt Trauma (BABT) [1]. The phenomenon is widely known, although the mechanisms of interaction between the generated pressure waves and the internal organs were not sufficiently explained and understood. The reason lies in the complexity of the human body structure, dynamics of the process as well as the difficulties in the observations and the measurement methodology. There are four main ways to obtain a direct injury data related to BABT [1]:

- ballistic tests on human cadavers;
- ballistic tests on a living animals;
- ballistic tests on volunteers;
- human epidemiology analysis.

All of the methods have significant disadvantages. The main weak point of tests on animals is that the appropriate scaling relationship between the injuries in animal and human has not yet been determined. Taking into consideration the significant differences in both anatomies it is not an obvious task. The volunteers can be tested only below the injury thresholds. Epidemiological data is often incomplete, there is a lack of information about the basic parameters of impact, such as: shooting distance, impact velocity, angle of impact etc. The most reliable data may be collected during the experiments carried out on cadavers - Post Mortem Human Subjects (PMHS). Such test were carried out in the works [2-6] where the response corridors to the specific loads as well as the injury criterions were determined. But the tests were performed mainly for the needs of the automotive industry. The impact velocities (5÷60 m/s) were significantly lower than that of ordinary projectiles (300÷900 m/s). The high-speed ballistic tests on human cadavers should be carried out to better understand the BABT and injury mechanisms. Taking into consideration considerable time involvement and serious ethical issues, it is difficult to carry out ballistic tests on PMHS. Therefore in current methodology of BABT investigation, specific materials and systems are used that simulate the human tissues behavior. The human body surrogates used in ballistic tests may be divided into three groups:

- backing materials - single material that simulates the soft tissues of human body (e.g. ballistic clay or ballistic gelatin);
- simple anatomical surrogates - more complex than backing materials, may consist of multiple layers (e.g. synthetic bones surrounded by ballistic gelatin and covered by skin surrogate);
- detailed anatomical surrogates - sophisticated anatomical systems consisting advanced measuring equipment to register a wide range of parameters (pressure, force, acceleration).

An effective body surrogate should be as simple as possible. However the simulant should provide a proper reproduction of the characteristic human response to the specific loads with a maximum repeatability. Detailed anatomical surrogates provide the greater amount of information, but taking into consideration highly destructive character of the ballistic tests and high costs of the system they are not used very often. The backing materials are the most frequently used human body surrogates in the current experimental methodology of evaluating body armor effectiveness. There are two main types of backing materials:

- ballistic clay (Roma Plastilina n°1);
- ballistic gelatin (10% or 20%).

The armor is placed on the block made of backing material and impacted with specific projectiles. After six shots (appropriate distances between the shots must be kept) the indentation in the backing material is measured and compared to the acceptable value-BFD=44 mm (Back Face Deformation). The methodology based on BFD criterion is fast and robust, although it seems to be too simplified and has a few significant weak points, e.g.:

- the measured indentation in clay does not give any information about the level of injuries in the human body, because there is no empirical correlation between the BFD and a probability for lethality or injury.
- regarding the viscoelastic behavior of the human tissues it is reasonable to analyze not only the deformation value but also the velocity of deformation (strain rate) that can be very high in case of ballistic impacts.
- in contrast to the ballistic clay in case of the human thorax the location of impact is important.

Taking into consideration the mentioned disadvantages and limitations it seems to be reasonable to look for other techniques that could support the laboratory investigation of BABT. The numerical methods have a large potential in this matter and can constitute an interesting alternative. Supporting the BABT experimental investigation with the finite element modeling may allow for better understanding of the mechanisms occurring during the high-velocity projectile impact phenomenon. Constant development of computer science especially the growth of computational power has made it possible to simulate the behavior of not only single backing materials but large complicated systems of interacting components such as the human thorax as well. In the situation when the regular ballistic tests on the cadavers are almost impossible to carry out, the detailed and well validated numerical model of the human body could be an efficient tool, helpful in the establishment of:

- the injury risk model;
- the relationship correlating deformation in backing materials with the injury level in the human body.

In the future it may lead to development of more accurate methodology of BABT investigation that will link together experiments on human cadavers, field injury epidemiology and well-validated finite-element simulations. It may result in development of better designs of personal protections.
The possibility of numerical reproduction of the characteristic behavior of human body and backing materials under projectile impact was analyzed in the article. The numerical models of the ballistic clay, ballistic gelatin and the examples of their applications were shown. The validation process of the developed numerical model of the human thorax was described.

2 Numerical model of the ballistic clay

Roma Plastilina No1 is a homogenous, oil based ballistic clay. The material is defined as linear elastic-ideal plastic, but the level of its elastic recovery is so small that it can be neglected. Therefore, it can be assumed that under the loading the clay deforms plastically, and a permanent cavity in the zone of impact reproduces the BFD of the armor. The general behavior of the clay under the ballistic impact is significantly different than that of the human soft tissues,although it constitute a basic backing material in current experimental methodologies. The clay is cheap, reusable and repeatable. Additionally, the dimensions of the permanent cavity in the clay can be correlated to injury and lethality probability. Unfortunately the direct relationship between the depth of deformation in clay and an injury level in human body has not yet been determined. There are only imperfect and uncertain correlations between the BFD and a medical data of animals. The calibration of the clay is carried out by simple drop test to confirm a proper plasticity of the material. A cylindrical steel impactor with the spherical frontal part, a mass of 1 kg and a diameter of 44 mm is dropped from the height of 2 m on the clay placed in a container. The indentation in clay is measured and compared to the proper value: 25±3 mm.
Two types of simulations with the use of numerical model of ballistic clay were presented in the article. Numerical reproduction of the clay calibration test and the simulation of the 9x19 mm Parabellum projectile impact on the 16 UHMWPE layers placed on the container filled with the clay. Two symmetry planes were used to decrease the required time of computations. The quarter of the clay was meshed by 444 000 8-node constant-stress solid elements with one integration point and stiffness-based hourglass control. The element size was refined in the impact zone and was 0.4x0.4x0.4 mm. The discretization of the clay into finite elements was shown in Fig. 1.
***MAT_018-POWER_LAW_PLASTICITY** was used to describe the behavior of the clay. This is an isotropic plasticity model with rate effects which uses a power law hardening rule [7]. The parameters of the material model (Table 1) were adopted on the basis of the work [8].
The friction between the impactor and the clay was not considered. Contact between the components was modelled by ***CONTACT-ERODING_SURFACE_TO_SURFACE** algorithm. The results of calibration simulation were shown in Fig. 2. The obtained indentation in clay equaled 26 mm, and was within the acceptable range.

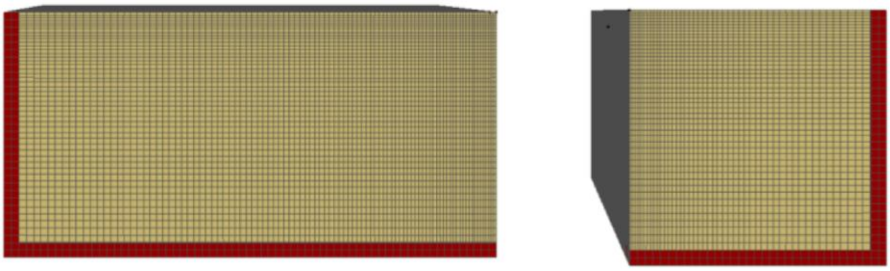

Fig.1: Discretization of the ballistic clay in the container

RO, Tonnes	E, MPa	PR	K, MPa	N	SRC	SRP	SIGY	EPSF	VP
1.878	14.2	0.49	0.24	0.0140	0	0	0	2.5	1

*Table 1: Parameters of the *MAT_018-POWER_LAW_PLASTICITY model for the clay*

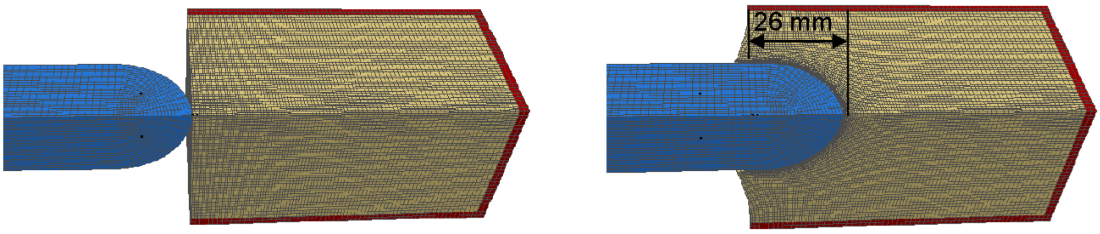

Fig.2: The results of numerical reproduction of the clay calibration tests

In the second type of simulation the 9x19 mm Parabellum projectile impacted the 16 ultra-high molecular weight polyethylene (UHMWPE) soft layers placed on the container filled with the clay. The quarter of the projectile was meshed regularly with the use of 30600 8-node constant-stress solid elements with one integration point and stiffness-based hourglass control (Fig. 3). The elastic-plastic behavior of the projectile parts was described by **`*MAT_107-MODIFIED_JOHNSON_COOK`** card. The parameters of the material model were collected in Table 2. Contact between the lead core and the brass jacket of the projectile was assumed to be frictionless and was realized by **`*CONTACT-ERODING_SURFACE_TO_SURFACE`** algorithm.

	RO, Tonnes	E, MPa	PR	A, MPa	B, MPa	n	C	m	D1	D2	D3	D4	D5
Lead	1.01e-8	18400	0.42	24	40	1	0.01	1	3	0	0	0	0
Brass	8.52e-9	115000	0.31	206	899	0.42	0.01	1.68	**WC**		1414		

*Table 2: Parameters of the *MAT_107-MODIFIED_JOHNSON_COOK model for projectile parts*

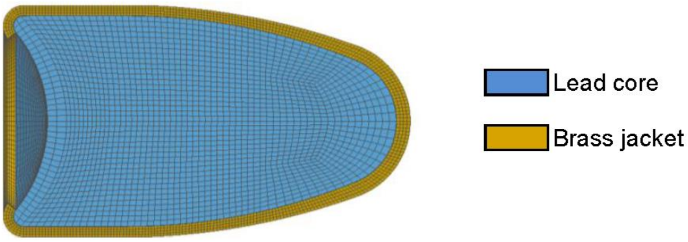

Fig.3: The discretization of the 9x19mm Parabellum projectile

The projectile was validated on the basis of experimental data. The ballistic tests of the projectile impact into the polished thick steel plate at different velocities (50 – 150 m/s) were carried out in order to check the behavior of the projectile at different deformation rates - from low deformation up to the failure of the brass jacket. The results of the validation tests were shown in Fig. 4. The obtained results confirm that the adopted parameters provide correct behavior of the projectile in the analyzed velocity range.

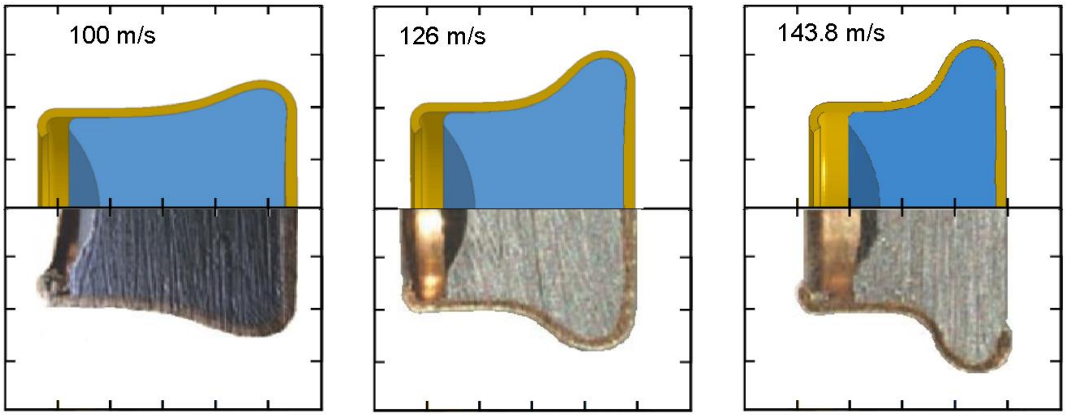

Fig.4: Results of the 9x19mm Parabellum projectile validation tests

The (UHMWPE) soft layers were modelled by quadrilateral fully integrated shell elements. Each layer was meshed independently with 10000 of elements. ***MAT_003-PLASTIC_KINEMATIC** was used to describe the layers. The parameters of the material model (Table 3) were adopted on the basis of the work [9]. Contacts between the layers and other components were modelled by ***CONTACT-ERODING_SURFACE_TO_SURFACE** algorithm.

RO, Tonnes	E, MPa	PR	SIGY, MPa	ETAN, MPa	BETA	SRC	SRP	FS	VP
9.62e-10	21330	0.27	320	7040	0	0	1	0	1

*Table 3: Parameters of the *MAT_003-PLASTIC_KINEMATIC model for UHMWPE soft layers*

The results of simulation of the 9x19 mm Parabellum projectile impact into the 16 ultra-high molecular weight polyethylene (UHMWPE) layers placed on the container filled with a clay as well as its experimental equivalent were shown in Fig. 5. There were some visible differences between the simulation outcomes and the experimental results. The BFD in the simulation was about 30% lower than in ballistic tests. It may be caused by the fact that the impact velocity of projectile was not measured during the tests and could be higher than in the simulations. Moreover, the UHMWPE soft layers material model was adopted on the basis of literature data without any additional validation. But the general behavior of the numerical model of ballistic clay was similar to those observed during the experiments.

Fig.5: The results of simulations and experiments of the 9x19 mm Parabellum projectile impact into the 16 UHMWPE layers:a – indentation in clay; b – front of the sample; c – projectile after the test

3 Numerical model of the ballistic gelatin

Ballistic gelatin is a mix of a gelatin powder (10% or 20%) and water. The elastic material simulates the density and viscosity of soft human tissues. Thanks to the high transparency and high elastic recovery level in the unloading phase, the gelatin is preferred for penetrating injury studies as well as for reproduction of temporal cavities and projectiles flight paths inside the human body. Gelatin is more inconvenient to use in the ballistic tests than clay. High speed recording systems are required for observation of its behavior. Due to the high temperature sensitivity gelatin has to be cooled and stored in a low temperature (about 4°C). The temperature of the material has to be constantly controlled to provide equal density during subsequent shots. Ballistic gelatin is not reusable. The calibration of the

gelatin block is carried out by impact of a 4.5 mm caliber steel fragment with a velocity of 183 ± 3 m/s. The depth of penetration of the block is measured and compared to the proper value DoP=83-95 mm.
Two types of simulations with the use of numerical model of ballistic gelatin were presented in the article: numerical reproduction of the gelatin calibration test and the simulation of 7.62x39 mm PS projectile penetration of the gelatin block. A single symmetry plane was used to speed up the computations. The half of the gelatin block was modeled with the use of 4 450 000 8-node constant-stress solid elements with one integration point and stiffness-based hourglass control. The mesh was refined in the impact zone to the element size of 0.7x0.7x0.7 mm. The discretization of the gelatin block into the finite elements was shown in Fig. 6. ***MAT_010-ELASTIC_PLASTIC_HYDRO** combined with ***EOS_LINEAR_POLYNOMIAL** equation of state was used to describe the behavior of gelatin. This material allows the modeling of an elastic-plastic hydrodynamic material with pressure-dependent yield behavior [7]. The parameters of the material model adopted on the basis of the work [10] were collected in Table 4.

RO, Tonnes	G, MPa	SIGY, MPa	EH	PC	FS	CHARL	C1	C2	C3
1.030e-9	0.85	0.22	0.001	0.0140	0.9	0.0	2380	7140	11900

*Table 4: Parameters of the *MAT_010-ELASTIC_PLASTIC_HYDRO model for gelatin*

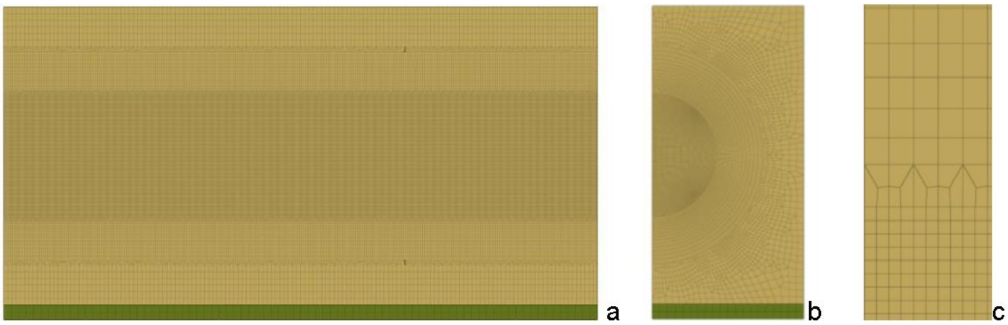

Fig.6: Discretization of gelatin block into finite elements: a – side, b – front, c – mesh transition method

Contacts between the impactors and the gelatin were assumed to be frictionless and were modelled by ***CONTACT-ERODING_SURFACE_TO_SURFACE** algorithm. The results of the gelatin calibration simulation were shown in Fig. 7. The obtained depth of penetration in gelatin (8.54 mm) was within the acceptable range.

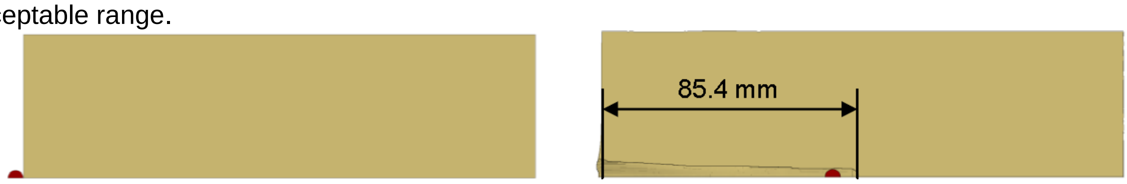

Fig.7: Numerical reproduction of the gelatin calibration tests

The projectile FE model was composed of 14 820 8-node constant-stress solid elements with one integration point and stiffness-based hourglass control (Fig. 8). Since the projectile was not significantly deformed during the corresponding experimental tests, the parameters of the ***MAT_107-MODIFIED_JOHNSON_COOK** material model (Table 5), were adopted on the basis of the literature data [10] without any additional validation. Contacts between the components of simulation were assumed to be frictionless and were modeled by ***CONTACT-ERODING_SURFACE_TO_SURFACE** algorithm.

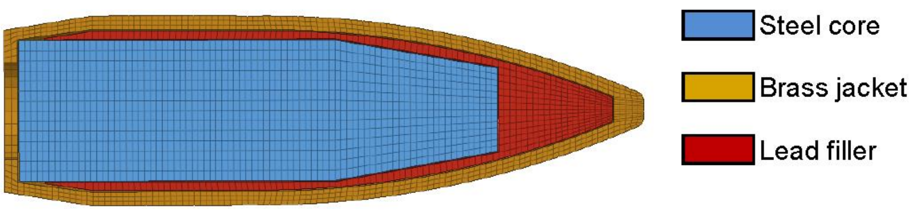

Fig.8: Discretization of the 7.62mm PS projetile into finite elements

	RO, Tonnes	E, MPa	PR	A, MPa	B, MPa	n	C	m
Lead	11.34e-9	14.2	0.42	14	17.6	0.014	0.28	1.03
Brass	7.92e-9	210000	0.33	792	510	0.685	0.035	1.68
Steel	7.83e-9	210000	0.33	792	510	0.014	0.28	1.03

*Table 5: Parameters of the *MAT_107-MODIFIED_JOHNSON_COOK model for projectile*

The results of simulation of the 7.62x39 mm PS projectile penetration into the gelatin block (40x25cm) were shown in Fig. 9. The model of the gelatin provide accurate reproduction of the temporal cavity in the block.

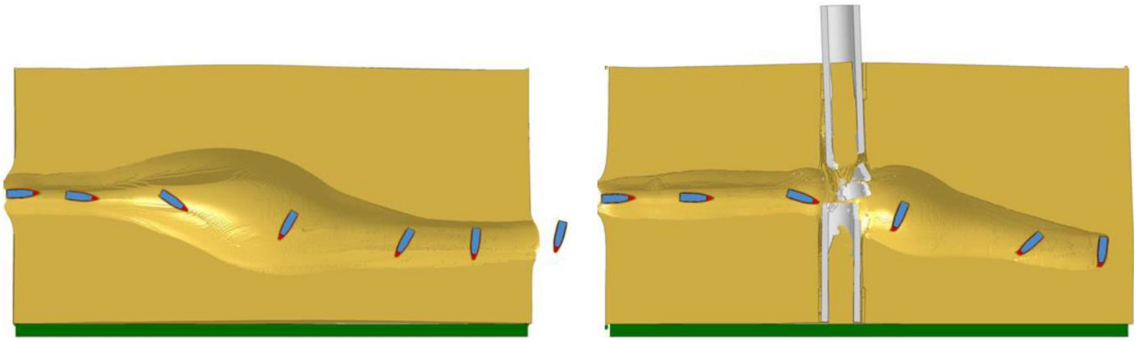

Fig.9: Simulation of 7.62x39mm PS projectile penetration of the: a -clear gelatin block, b – gelatin block with a synthetic bone embedded

4 Numerical model of the human torso

The human thorax is a very complex structure. Highly non-linear orthotropic behavior of the materials, various shapes of the components and sophisticated interactions between the bones, muscles and internal organs make it difficult to reproduce the biomechanical response of the system to the impact with the use of finite element modeling. Even though a rapid development of the computer science and the growth of the computational power is observed, still a lot of assumptions and simplifications have to be made during the development of a numerical model of the human body. However, numerical methods can be really helpful in the investigations of highly dynamic phenomena e.g. projectile impacts. Simulations allow collecting a lot of data that would be difficult or even impossible to obtain during the experiments (internal pressures, stresses, strains and displacements). Therefore an attempt was made to develop the numerical model of the human thorax that will support the investigations of the BABT phenomenon.

4.1 Geometry of the model

The numerical model of the human thorax was built in Altair Hypermesh® software and is dedicated for the LS-Dyna® solver. The model accurately reproduces the main anatomical characteristics of a 30-year old male with a height of 180 cm, a weight of 80.0 kg and a BMI of 25.8. It consist of detailed representation of skin, skeleton, muscle system and all the crucial internal organs (Fig. 10). The model contain about 400000 nodes, 200000 8-node solid elements and 22000 quadrilateral shell elements. Additionally 162000 SPH particles are used to represent the internal fluids. The hollow organ such as lungs, heart, stomach, intestines, as well as the space between the organs are filled with SPH particles representing air, blood, water, etc. All the bones in the model are composed of two types of structure: the trabecular bone inside and the cortical bone on the outer surface of the bone. Both tissues are modelled by solid elements.
The constitutive equations adopted for the model were selected on the basis of the data available in the literature [11-16]. Skin, diaphragm and some internal organs were modelled by **`*MAT_001-ELASTIC`** material. Other internal organs as well as the muscles were described by **`*MAT_006-VISCOELASTIC`** card. To accurately capture the response of bones the card **`*MAT_003-PLASTIC_KINEMATIC`** was selected. Blood, air and other body fluids were represented by **`*MAT_001-FLUID-ELASTIC_FLUID`**. Because the model has to reproduce the failure of the materials during the high speed impacts the appropriate erosion criteria were adopted by **`*MAT_000-ADD_EROSION`** card. Fracture criteria for the materials were based mainly on the limiting values of principal stresses and strains. Material properties adopted from the literature [11-16] were modified in order to obtain a correct model response during the validation process.

The thorax model consist of 84 individually meshed parts joined together with shared nodes, discrete elements and appropriate contact algorithms. The contact between the fluids (air, blood, internal fluid) particles and the solid elements of other components were modelled by ***CONTACT-ERODING_NODES_TO_SURFACE** algorithm. The specific internal organs as well as the bones and muscles were joined together by ***CONTACT-AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK** with the appropriate values of normal and shear stresses that breaks the connection. Additionally, in some cases the nodes at boundary surfaces of joined components, e.g. cortical and trabecular parts of the bones were shared. ***CONTACT-ERODING_SURFACE_TO_SURFACE** algorithm was used in the case were failure of the elements as well as penetration between the components were predicted: e.g. between the impactors and the body. It was assumed that no friction occurs between the contacting surfaces.

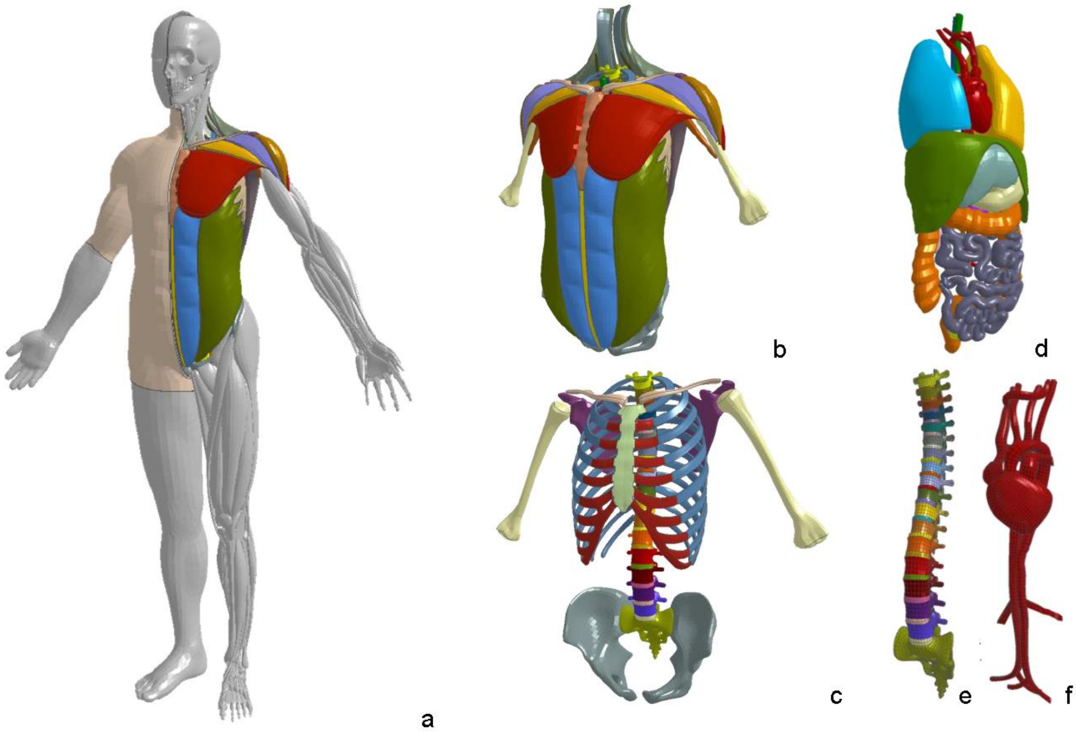

Fig.10: Developed finite element model of the human body: a – section of the body, b– muscle system, c-skeletal system, d-internal organs, e-spine, f-heart

4.2 Validation of the model

The model was validated by comparing its mechanical response to the acceptable corridors established during the impact tests carried out on PMHS [2-6]. Different types of impact scenarios were reproduced using the model, and subsequently the shapes of force-displacement (compression) curves obtained numerically and experimentally were compared. In the experiments the impact force was measured by a load cell installed on the frontal surface of the impactor. High speed cameras were used to measure the deflection of the body. Displacement of the two gauge points located on the opposite sides of the body was registered and the difference in the displacement values constituted the compression of the body. In the simulations the force was registered as a reaction force in the contact between the impactor and the skin. Compression was measured analogically as in the experiments as a distance between the nodes on the opposite sides of the thorax.
In the frontal pendulum test a rigid cylindrical impactor with a diameter of 150mm and a mass of 23.4 kg impacted the sitting cadaver, with no back support. The longitudinal axis of the impactor pointed to the center of the sternum between 4th and 5th rib. The impact velocity was 6.7 m/s. The force-compression curve obtained in the simulations was within the acceptable corridor (Fig. 11). The fracture of the ribs located in the lower part of the sternum were observed in the simulations.

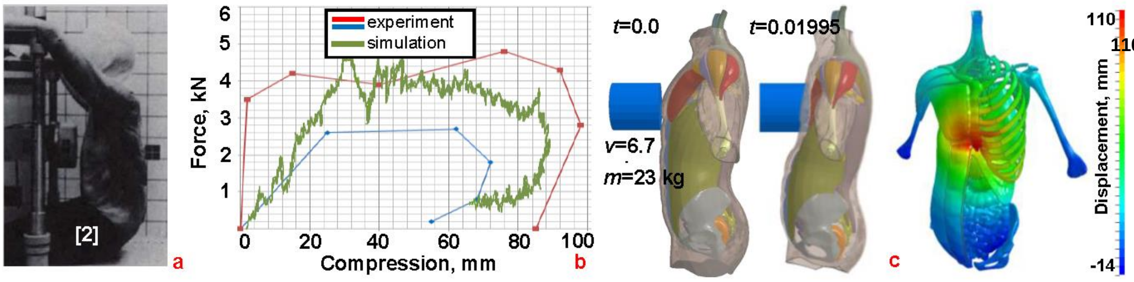

Fig.11: The results of the frontal pendulum validation test: a - experiment set-up [2], b - force-compression curves, simulation results

In the lateral pendulum test carried out by Chung et.al [4] the wood impactor with a mass of 50 kg and a diameter of 152.4 mm impacted the lateral center of the sternum on the level of the sixth rib. The cadaver movement was restricted. The impact velocity equaled 5.6 m/s (Fig. 12).

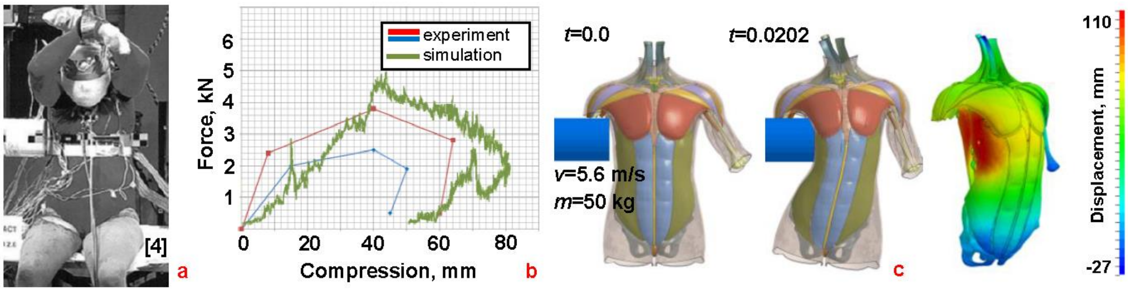

Fig.12: The results of the lateral pendulum validation test: a - experiment set-up [4], b - force-compression curves, simulation results

To check the response of the abdominal part of the thorax to the impact, the tests carried out by Cavanaugh et. al. [5] were reproduced. The aluminum bar (diameter: 25 mm, mass: 32 kg) impacted the abdomen of PMHS horizontally at an initial velocity of 6.1 m/s (Fig. 13).

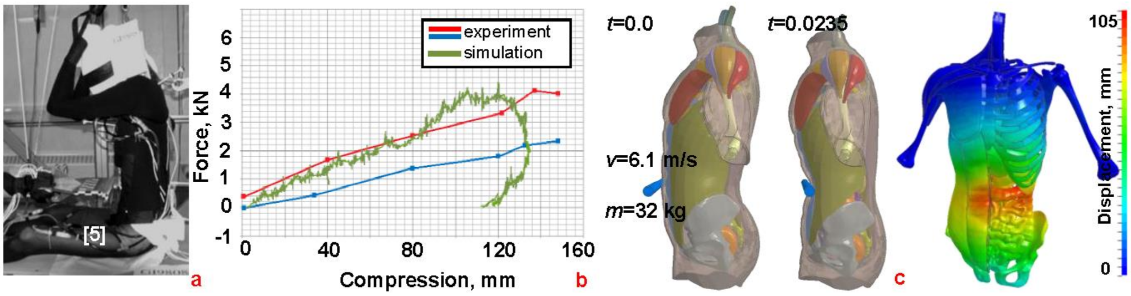

Fig.13: The results of the abdominal frontal impact validation test: a - experiment set-up [5], b - force-compression curves, c - simulation results

To check the behavior of the thorax model during the impact of smaller impactors at higher velocities the tests carried out by Bir [6] were modelled. In the first variant of the test the cylindrical impactor with mass of 30g hit the center of the sternum at an initial velocity of 60 m/s (Fig. 14).

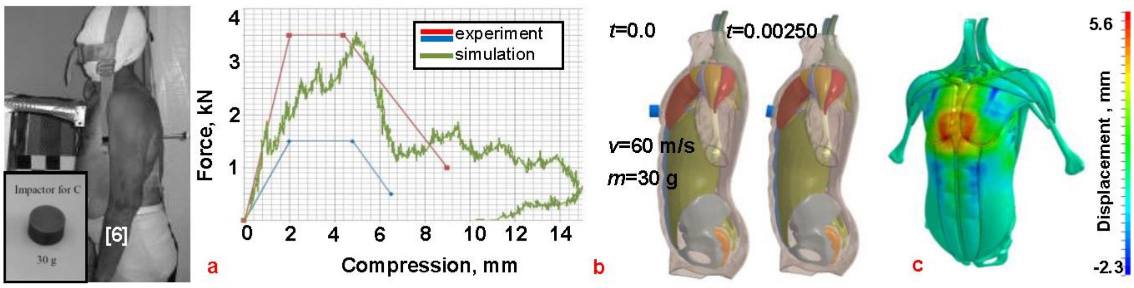

Fig.14: The results of the frontal impact validation test according to Bir [6], impactor C: a - experiment set-up [6], b - force-compression curves, c - simulation results

In the second variant of the Bir test [6] the cylindrical impactor with a mass of 140 g hit in the middle of the sternum at an initial velocity of 40 m/s. The experimentally determined corridor was large and the response of the numerical model was close to its lower border (Fig. 15).

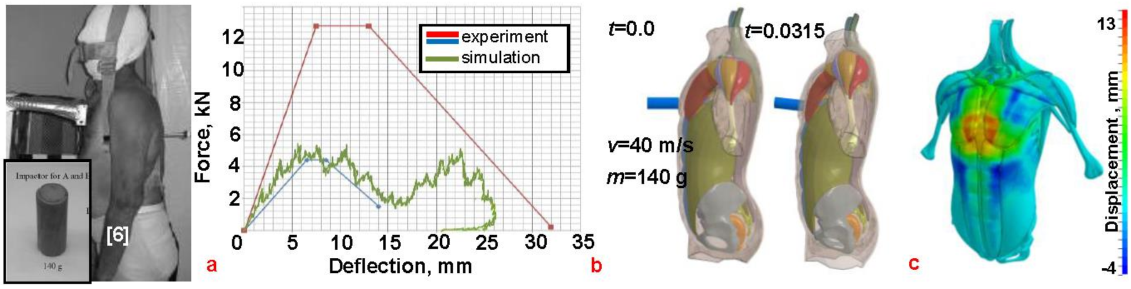

Fig.15: The results of the frontal impact validation test according to Bir [6], impactor A/B: a - experiment set-up [6], b - force-compression curves, c - simulation results

Generally the responses of the numerical model of the human thorax for the specific loads showed satisfying correlation with the experimental observations. The model has the possibility to accurately predict the risks of injuries in the analyzed velocity range.

5 Summary

Computational models for the backing materials (ballistic clay and ballistic gelatin) simulating soft human tissues and for the human thorax were presented in the article. The models were created in order to support the experimental methodology of investigating of the BABT phenomenon. The models were validated against the experimental data. Their responses for the specific loads showed satisfying correlation with the experimental observations. Supporting the experimental investigations with the finite element modeling may help to avoid the inconvenience experienced during the laboratory tests and allows for better understanding of the mechanisms occurring during the analyzed BABT phenomenon.

The numerical model of the human thorax showed high correlation with the available impact corridors. and has the possibility to predict the risks of bone fractures and internal organs injuries in the analyzed velocity range. But the main limitation of the model is the lack of validation for the impact conditions specific for the ordinary projectiles and BABT phenomenon (low mass and high velocity of impactors). Therefore additional cadaveric experiments carried out in a high velocity-impact conditions or accurate epidemiology data including all the required information about the parameters of the impacts are required to validate the model at strain-rates characteristic for the projectile-body armour interaction. A well validated numerical model will be helpful in a better understanding of the injury mechanisms. It will be used to establish a BABT injury criterion and to determine the correlation relationship between the clay indentation and the injury level in the human body at the analyzed strain rates. The future works include also the validation of the local dynamic response of the body components, bones, muscles, lungs, and other tissues.

6 Literature

[1] Committee on Testing of Body Armor Materials for Use by the U.S. Army: "Testing of Body Armor Materials Phase III", The National Academies Press, Washington, ISBN 978-0-309-25599-8

[2] Kroell, C.K., Schneider, D.C. Nahum, A.M: "Impact tolerance and response of the human thorax", 15th Stapp Car Crash Conference Proceedings, SAE, 1971

[3] Kroell, C.K., Schneider, D.C., Nahum, A.M: Impact tolerance and response of the human thorax II. 18th Stapp Car Crash Conference Proceedings, SAE, 1974

[4] Chung, J., Cavanaugh, J. M., King, A., Koh, S-W., Deng, Y-C: "Thoracic injury mechanisms and biomechanical responses in lateral velocity pulse impacts", 43rd Stapp Car Crash Conference Proceedings, SAE, 1999

[5] Cavanaugh, J., Nyquist, G., Goldberg, S., King, A: "Lower Abdominal Tolerance and Response", 30th Stapp Car Crash Conference Proceedings, SAE, 1986

[6] Bir, C: "The evaluation of blunt ballistic impacts of the thorax", PhD thesis, Wayne State University, Detroit Michigan, 2000

[7] LS-Dyna® Keyword User's Manual, Volume II, Material Models, 03/07/19, Livermore Software Technology Corporation (LSTC)

[8] Hernandez, C., Maranon, A., Ashcroft, I.A., Casas-Rodriguez, J.P: "Inverse methods for the mechanical characterization of materials at high strain rates", EPJ Web of Conferences 26, 2012
[9] Alil, L.C., Matache, L.C., Sandu, S.M: "Numerical Simulation of a Ballistic Impact on Tensylon® UHMWPE Laminates Using the Plastic Kinematic Model in LS-Dyna®", Journal of Military Technology, Vol. 1, No. 1, 2018
[10] Wen, Y., Xu, C., Jin, Y., Batra, R.C: "Rifle bullet penetration into ballistic gelatin", Journal of the Mechanical behavior of biomedical materials 67, 2017, 40-50
[11] Cai, Z., Lan, F., Chen, J., Zhao, F: "Development and Validation of a Finite Element Model of the Human Thoracic for Rib Fractures Prediction in Automobile Collisions", Proceedings of the Fisita 2012 World Automotive Congress, Heidelberg, 2013
[12] Li, Z., Kindig, M.W., Kerrigan, J.R., Untaroiu, C.D., Subit, D., Crandall, J.R., Kent, R.W: "Rib fractures under anterior-posterior dynamic loads: experimental and finite-element study", J. Biomech 43(2), 2010, 228–234
[13] Ruan, J., El-Jawahri, R., Raed, E: "Analysis of human thoracic impact responses and injuries in cadaver impacts using a full human body finite element model", Stapp Car Crash J, 47, 2003 299–321
[14] Kemper, A.R., McNally, C., Kennedy, E.A., Manoogian, S.J., Rath, A.L., Stitzel, J.D., Smith, E.P., Duma, S.M: "Material properties of human rib cortical bone from dynamic tension coupon testing", Stapp Car Crash J, 49, 2007, 199–230
[15] Kemper, A.R., McNally, C., Pullins, C.A., Freeman, L.J., Duma, S: "The biomechanics of human ribs: material and structural properties from dynamic tension and bending tests", Stapp Car Crash J, 51, 2007, 235–273
[16] Yamada, H: "Strength of Biological Materials", FG. Evean, Ed., The Williams & Wilkins Company, Baltimore, 1970