The fluid-based structure for human body impact protection

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Abstract. The article presents results of research and analysis of the currently conducted project aiming at the development of a flexible impact protector. The need to carry out the work results from the necessity of the ever-wider and more frequent use of body armours, including those resistant to blunt impacts, by the army, police and other public security services as well as a demand for impact protective elements in the civilian market. In the first part, the assumptions regarding the protective coverage under development and the origin of the topic with reference to earlier work on the use of non-Newtonian fluids in body armours are indicated. Next, the requirements for impact protectors and a review of the state of the art in the scope of this type of protective elements are presented. Finally, the results of the impact tests of armour samples are shown.

1. Introduction

The aim of the currently presented research is to investigate the possibility of using fluid-based structures as flexible impact protectors. The need to carry out the work results from the necessity of the ever-wider and more frequent use of body armours, including those resistant to blunt impacts, by the army, police and other public security services as well as a demand for impact protective elements in the civilian market. A diagram presenting the genesis of the subject is shown in figure 1.

The first research works of Military Institute of Armament Technology (MIAT) on using non-Newtonian fluids for human body protection were performed in the years 2009–2014 within the framework of the project titled “Smart passive body armours with the use of rheological fluids with nanostructures” [1]. The project was realized in cooperation with the Faculty of Materials Science and Engineering of the Warsaw University of Technology and the Institute of Security Technology MORATEX. Ballistic protection tests (PN-V-8700:2011/K1A - 9x19 mm FMJS Parabellum [2]) of armour samples modified with shear thickening and magnetorheological fluids demonstrated capability of both the fluids (STF and MRF) to absorb and dissipate impact energy of the bullet and hence reduce the backface signature (BFS) [3]–[5]. A better protection capability with respect to mass was achieved for the STF, therefore the further works were concentrated exclusively on it.

After the completion of the Smart Armour project, the research was continued in 2015 within the MIAT statutory work financed from the own research fund Development of the flexible ballistic insert with the anti-trauma pad for a bulletproof vest. The aim of the research was to investigate protective capabilities of soft armour samples with the fluids (STF1 – shear thickening fluid based on silica nanoparticles dispersed in polypropylene glycol, KM – viscoelastic fluid based on homogeneous methyl-phenyl-borosiloxane polymer and ZB – viscoelastic polymer compound made of a high molecular weight polymer fluid with rheological modifiers) in the case of application of a stronger
penetrator than in the previously carried out project. The bulletproof tests were carried out according to the NIJ Standard-0101.04 for the IIIA class [6]. The works were focused on the 0.44 Magnum SJHP (semi-jacketed hollow point) projectile which causes, in this class of bullet resistance larger BFS. The penetrator impact energy is in this case nearly 1500 J and is almost three times higher than the energy of impact of 9 mm bullet, for which most bulletproof tests were performed in Smart Armour project. As part of the project conducted in 2015, different variants of anti-trauma pads with fluids were designed and their protective capability was compared in bulletproof tests to the pads available on the market [7]-[10]. From all the armour variants developed, the best ability to absorb impact energy and the greatest reduction of BFS in reference to mass were obtained for armour with anti-trauma pads in the form of:
- open-cell polyurethane foam filled with viscoelastic fluid KM (areal density $A_d = 5.08$ kg/m$^2$; average indentation in the backing material $BFS_{av} = 35.8$ mm);
- foam made with the addition of STF fluid ($A_d = 4.98$ kg/m$^2$; $BFS_{av} = 38.8$ mm).

The aim of the currently conducted research is to investigate the possibility of using the previously selected variants of protective structures and new material systems as flexible impact protectors. Such an armour in different variants could be used as:
1) protective clothing for horse riders;
2) protective clothing for motorcyclists;
3) impact protectors for public security services.

![Diagram of the genesis of the subject.](image-url)
2. Blunt force trauma personal protective equipment

Various types of blunt force trauma personal protective equipment for police officers, horse riders and motorcyclists were analysed. Elements for impact energy absorption in their construction are mostly based on low density susceptible soft materials. The most commonly used materials of this type are: Poron® XRD open-cell polyurethane foams, elastomers and foams made from non-Newtonian D3o® substance, visco-elastic foams with shape memory produced by SAS-TEC® and based on shear thickening polymer Zombug® material. Along with them, semi-flexible plastic molded parts (e.g. ABS - acrylonitrile-butadiene-styrene terpolymer, PC - polycarbonate) are often used. Owing to these more rigid elements, it is possible to dissipate impact energy into a larger area and protect soft energy-cushioning materials against mechanical damage.

Different blunt force impact protectors dedicated to public security services are shown in figure 2.

Figure 2. Blunt force impact protectors, dedicated to public security services based on plastic molded plates combined with: a) open-cell polyurethane foam [11], b) D3o® [12], c) 3D cushioning textile structure [27th International Defence Industry Exhibition MSPO 2019 - Poland/Kielce].

3. Materials and methods

3.1. Materials

The current stage of work is focused on construction of impact energy soft cushioning elements. Due to the potential of non-Newtonian fluids recognised in the works conducted earlier it was decided to try to develop blunt force impact protectors based on them. The work was mainly concentrated on two materials: the shear thickening fluid STF developed under the Smart Armour project (based on silica nanoparticles dispersed in polypropylene glycol) and viscoelastic material used in railway dampers to absorb impact energy (based on homogeneous methyl-phenyl-borosiloxane polymer). The development of protectors providing the desired protective effectiveness with the minimized share of rigid elements, with the highest possible comfort of use, through application of light, soft and flexible elements, was assumed.

The following types of armour samples with dimensions 70x70 mm were prepared for drop tests:

I. Developed material systems

1) polyurethane foams based on dedicated mixture composition (without STF fluid);
2) polyurethane foams based on mixture composition modified with the addition of shear thickening fluid (two types of addition investigated: STFA with fumed nanosilica content by volume equal to 40%; STFB with amorphous nanosilica content by volume equal to 50%);
3) commercial open-celled polyurethane foams for high energy-absorption applications combined with viscoelastic fluid KM.

II. Reference samples are commercial open-celled polyurethane foams for personal protective equipment. For I/3 material system, the following variants of samples were prepared (content of the ingredients given by mass):

- 100% viscoelastic fluid KM;
- 87% viscoelastic fluid KM + 13% commercial open-celled polyurethane foam (144 kg/m³);
- 82% viscoelastic fluid KM + 18% commercial open-celled polyurethane foam (144 kg/m³);
- 69% viscoelastic fluid KM + 31% commercial open-celled polyurethane foam (144 kg/m³).

Figure 3 presents a diagram illustrating the whole range of the prepared samples.

**Figure 3.** The range of armour samples (protectors) prepared for the drop test.
3.2. Methods

Depending on application, specific requirements regarding protective capability are formulated for the blunt trauma protectors [13]-[15]. Research methods allowing its determination usually involve the use of a Drop Tower device. The test, however, consists in dropping an impactor (of a given weight and shape) with a specific energy onto a sample placed on an anvil with a certain curvature. During the test, the force transmitted under the tested sample onto the anvil is measured with a piezoelectric sensor. Its maximum value over time $F_{\text{max}}$ defines whether the protective element provides the desired level of protection.

The scope of the drop tests described in the paper is presented in figure 4.

![Test stand diagram](image)

Blunt impact protectors dedicated to public security services

Exemplary antiriot suit [16]

4 types of impactor combined mass with metal carriage $m_c = 15$ kg
Impact energy $E_i = 195$ J

Future work

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**Figure 4.** Diagram of the carried out tests and the future works.
Personal protective equipment intended for public security services (e.g. Police) is usually tested in accordance with the standard BS 7971-8:2003 in which impact energy for torso protectors equals 20±1 J. Research carried out at the Faculty of Mechanical Engineering, the Military University of Technology, described in [17], indicates that this energy is not adequate to the threats to which the Policeman is exposed in real conditions. Paper [17] states that the impact energies resulting from the use of the most common tools of violence in riots, such as stone, flat board, baseball bat or paving stones, can reach up to 195 J.

In the first tests carried out jointly by MIAT and MUT, it was decided to test, in accordance with the methodology described in [17], the resistance of the armour samples prepared in MIAT to the effect of a flat impactor with impact energy in the range of 50 ÷ 96 J (figure 4). As a requirement for the blunt impact protectors under development for $E_i = 50 \text{ J}$ and $E_i = 96 \text{ J}$ the acceptable values of maximal transmitted force were assumed as $F_{\text{max}} \leq 4 \text{ kN}$, $F_{\text{max}} \leq 9 \text{ kN}$, respectively.

The best variants of material systems, selected in the experiments for $E_i = 50 \div 96 \text{ J}$, will be tested for higher impact energy ($96 \text{ J} < E_i \leq 196 \text{ J}$) and examined against the other three types of impactor ($50 \text{ J} < E_i \leq 196 \text{ J}$).

4. Results
The results of resistance tests of the developed material systems and reference samples to the influence of the flat impactor, with an impact energy of 50 J and 96 J, are presented in Table 1 and figures 5-6.

For an impact energy of 50 J, the lowest values of maximum forces $F_{\text{max}}$ transmitted under the anvil (evidence of the best protective capability) were obtained for commercial open-cell polyurethane foams with relatively low apparent densities equal to 96 and 144 kg/m$^3$.

In the case of impact energy equal to 96 J, better results were, however, recorded for material systems in which these foams were combined with viscoelastic fluid KM. Three variants of such a sample structure with the same areal density (5.2 kg/m$^2$) and different viscoelastic fluid content (69%, 82% and 87% for samples P1, P2 and P3, respectively) were tested. The highest protective ability (the lowest $F_{\text{max}}$ value) was obtained for P1 sample, in which 10 mm foam No. 1 (with apparent density equal 144 kg/m$^3$) was combined with viscoelastic fluid in mass ratio 31:69 (69% of KM). Compared to P4 sample, in which the same type of foam was used without the KM fluid, for P1 with three times smaller thickness and areal density smaller by 9%, $F_{\text{max}}$ reduced by 63% was obtained. Compared to sample P6B, in which a different type of foam was used for P1 material system, a similar value of maximum transmitted force (lower by 2.6%) was obtained at more than five times smaller thickness and an areal density lower by 18%.

After comparing P1 sample with P5 variant, in which standalone viscoelastic fluid without foam was used (sample of the same mass and 3 times smaller thickness), it was found out that for P5 the value of $F_{\text{max}}$ in the case of impact energy $E_i = 96 \text{ J}$ is lower by 7%, while for $E_i = 50 \text{ J}$ higher by 64%. The KM fluid itself can, therefore, provide a better protective capability for a higher impact energy than high-strength commercial polyurethane foams and composite samples, however for lower impact energy, it is not competitive in relation to them.

Considering the samples described, the most beneficial in terms of ensuring the assumed protective ability in the whole range of impact energy $E_i = 50\div96 \text{ J}$, high comfort of use and the functionality of the personal protective elements (also resulting from the thickness) is the use of P1 polyurethane foam system combined with viscoelastic fluid (69% of KM by weight).
Table 1. Drop test results for the flat impactor.

| Sample No. | Sample description                                                                 | Thickness, $t$, (mm) | Areal density, $A_d$, (kg/m$^2$) | Impact energy, $E_i$, (J) | Maximum transmitted force, $F_{max}$, (kN) |
|------------|-------------------------------------------------------------------------------------|----------------------|-----------------------------------|--------------------------|------------------------------------------|
| P4         | Standalone foam No. 1 (apparent density: 144 kg/m$^3$): 6 x 6 mm                    | 36                   | 5.74                             | 0.82                     | 23.09                                    |
| P6A        | Standalone foam No. 2 (apparent density: 96 kg/m$^3$): 2 x 21.7 mm                   | 43.4                 | 4.25                             | 0.52                     | 15.79                                    |
| P6B        | Standalone foam No. 2 (apparent density: 96 kg/m$^3$): 2 x 21.7 mm                   | 65.1                 | 6.34                             | -                        | 8.72                                     |
| P1         | 10 mm of foam No. 1 {31%} + 2.4 mm (3.77 kg/m$^3$) of viscoelastic fluid KM {69%} | < 12.4               | 5.20                             | 3.70                     | 8.49                                     |
| P2         | 6 mm of foam No. 1 {18%} + 2.7 mm (4.34 kg/m$^3$) of KM {82%}                      | < 8.7                | 5.20                             | 4.85                     | 9.12                                     |
| P3         | 4 mm of foam No. 1 {13%} + 2.9 mm (4.63 kg/m$^3$) of KM {87%}                      | < 6.9                | 5.20                             | 5.03                     | 8.77                                     |
| P5         | Standalone viscoelastic fluid KM {100%}                                             | 3 x 4                | 5.20                             | 6.07                     | 7.89                                     |
| P7         | Polyurethane foam PUR without addition of STF                                       | 12.7                 | 4.44                             | 3.30                     | 9.51                                     |
| P8         | PUR foam with the addition of STFB                                                   | 11.2                 | 4.40                             | 4.57                     | 10.83                                    |
| P9         | PUR foam with the addition of STFA                                                   | 14.5                 | 4.47                             | 4.30                     | 9.75                                     |

Figure 5. Drop test results for the flat impactor.
The second type of the tested armour samples were polyurethane foams with densities of 350 ÷ 450 kg/m³ made with and without the addition of the shear thickening fluid. The foams were based on a mixture composition developed in earlier conducted works. In the case of the bulletproof tests described in [7] for foams made with the addition of STFA in two variants of material systems (with polyethylene textile layers), compared to analogous variants of systems with foams without the addition of the shear thickening fluid, the indentations in the ballistic plasticine (BFS) smaller by 12% and 20% were obtained. Lower values of this parameter indicate a better ability to absorb impact energy of systems produced with the addition of STFA.

In the current research, two variants of modified polyurethane foams have been produced: with the addition of used in [7] STFA (with 40% fumed nanosilica content by volume equal to 40%) and with the addition of new kind of fluid - STFB (with amorphous nansosilica content by volume equal to 40%). In contrast to the protective capability tests described in [7] for the currently conducted type of test, the best results were obtained for foam without the addition of STF. The value of the maximum transmitted force $F_{\text{max}}$ for sample P7 was smaller in relation to the sample with STFA (P9) and STFB (P8):
- for $E = 50$ J by 23% and by 28%
- for $E = 96$ J by 3% and by 12%

It is evident that the difference in $F_{\text{max}}$ between foams without addition and foams with STF addition decreases with increasing impact energy. Further tests are planned to be carried out for impact energy higher than 96 J to verify whether this trend will continue and whether higher protective capabilities for foams made from STF addition will be obtained above a certain $E_i$ value as it was the case in the tests described in [7].

Figure 6. Drop test results for the flat impactor (transmitted force range from 3 to 10 kN).
5. Summary and conclusions

Resistance tests of different variants of armour samples to the free fall impact of the flat impactor with an impact energy of 50 J and 96 J were carried out. During the test, by a piezoelectric sensor, the force transmitted under the tested sample onto anvil was measured. On the basis of the maximum value of the force over time \( F_{\text{max}} \) (assuming for \( E_i = 50 \text{ J} \) and \( E_i = 96 \text{ J} \) the acceptable values \( F_{\text{max}} \leq 4 \text{ kN} \) and \( F_{\text{max}} \leq 9 \text{ kN} \), respectively) the best material systems were selected.

The following conclusions have been drawn:

1. In the case of impact tests of polyurethane foams produced with the addition of shear thickening fluid in the impact energy range up to 96 J, the addition of STF does not improve the ability to absorb kinetic energy.
2. For an impact energy of 50 J, the most beneficial is the use of open-cell polyurethane foams with relatively low apparent densities equal to 96±144 kg/m³.
3. For a higher impact energy (\( E_i = 96 \text{ J} \)), the lowest values of maximum forces \( F_{\text{max}} \) transmitted under the anvil (evidence of the best protective capability) can be obtained for viscoelastic fluid KM.
4. Among blunt impact protector variants with the same areal density and KM content of 69%, 82% and 87%, the best to use is the first one, in which the viscoelastic fluid is combined with 10 mm of foam with an apparent density of 144 kg/m³.
5. By combining the foam with the KM material it is possible to obtain a versatile protector, suitable for defeating the threats of a different energy level, which, owing to low thickness and flexibility, ensures high comfort of use.

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