Application of UHMWPE in energy-absorbing road safety systems

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Abstract. The article considers the possibility of using a polymer material based on ultra-high molecular weight polyethylene (UHMWPE) in energy-absorbing structures of road safety systems. To determine the mechanical and energy absorbing characteristics of the material, bench tests carried out on the material and element of the designed structure in the form of a thin-walled cylinder. The possibility of using UHMWPE in the actual design of the road safety system checked by creating a validated digital twin of the impact attenuator. Based on the simulation results, polymer and metal structures compared.

1. Introduction
Currently, there are more than 30 million kilometers of roads worldwide, and the number of registered vehicles reaches more than a billion, and this number growing at a rapid rate every year. Due to the significant increase in traffic intensity, mass of cars, speeds, as well as the length of the road network, the number of fatal accidents (accidents), injuries, economic and other dangerous consequences increased significantly in recent years.

The problem of ensuring road safety and reducing road mortality is especially highlighted [1]. Analyzing the statistics of accidents, it can be seen that in 2019 there were about 150000 such incidents, as a result of which about 190000 people injured, and about 18000 died. One of the main reasons for this victims number is the lack of various security systems types on many sections of roads.

The structures of most types of barriers until recently represented either by steel materials (side road barriers, wire rope barriers, frontal road barriers) or concrete (parapet barriers) [2]. However, in connection with the development of the chemical industry, it seems promising to develop road barriers designs using new polymer materials with a number of advantages: high energy absorption capacity, corrosion resistance, chemical inertia, low weight. The use of modern polymer materials can significantly improve the quality of existing structures road construction systems. We pay special attention to the sections of roads on which the road lane divided, since in this case the direction of the vehicle impact during an accident does not occur tangentially (at an average angle of 200), but perpendicular to the road barrier, which leads to serious consequences (figure 1).
The way out of this situation is the installation of additional fences – frontal barriers, designed to absorb the energy of frontal impact with minimal risks of severe injuries for passengers. Currently, the following are used as frontal traffic barriers:

1. Plastic enclosures filled with sand or water from the inside (figure 2). However, such a fence practically does not absorb the energy of the vehicle impact, and is installed mainly to inform road users about the separation of the road lane.

2. Designs with energy-absorbing elements in the form of metal honeycombs have become widespread (figure 3).

The SMA (Safety Modular Absorber) energy-absorbing enclosures use high-strength steel, which absorbs impact energy by plastic deformation of cells (hexagonal cells) installed inside the system. The use of a honeycomb absorbent structure ensures uniform energy absorption during the entire enclosure deformation process. With a frontal impact on a barrier 2.8 m long, a passenger car weighing 1500 kg at a speed of 100 km·h⁻¹, energy-absorbing honeycombs compressed, due to this the impact energy extinguished, the side barrier panels folded. The impact energy is 532 kJ. However, this design also has a number of drawbacks: the price of a metal structure, the need for corrosion protection, high inertia during operation. A way out of this situation may be the use of energy absorbing elements from, for example, polymeric materials.

In works [3, 4] quite detailed analysis of foreign structures of frontal barriers carried out. From this analysis, you can select the Guard LMC (figure 4).
Guard LMC has a length of 2.3 m. The guard consists of movable frames (diaphragms), which are surrounded by a movable side panel and energy absorbing elements - elastomeric cylinders. During frontal impact, the cylinders and side panels compressed, so that the vehicle slows down smoothly to a complete stop. The impact energy is 532 kJ. In addition, the elastomeric cylinders almost completely recover their shape after they discharged, and can be reused.

2. Materials and equipment

UHMPE considered as the material of the energy absorbing element. The determination of mechanical and strength characteristics carried out using a test machine with a force limit of 100 kN and a maximum loading speed of 1000 mm·min⁻¹. Tensile stress loading carried out at different loading rates (20-500 mm·min⁻¹). As a result of the experiment, the elongation amount of the sample fixed, as well as the force amount of resistance to the sample elongation. Based on the test results mechanical and strength characteristics determined, which reflected in [5]. The remaining characteristics determined from studies [6-8].

Determined the main mechanical characteristics of the UHMWPE, it decided to develop a barrier design with an energy absorbing element in the form of a cylinder (figure 5).

Compression tests performed to determine the energy absorption of such an element. The test diagram is shown in figure 6.
As a result of the full-scale experiment, a diagram of the force dependence on the movement of the active traverse of the test machine constructed (figure 7). Based on the results of experimental data on the diagram, the energy absorption amount was energy 0.326 kJ. The sample after the tests is shown in figure 8.

Analyzing the type of sample after the tests, noted that after three days the residual deformations were less than 10%, from which to conclude that with such a design, the energy absorbing element from the UHMWPE can be reused after significant deformations, unlike steel energy absorbing elements.

3. Model and methods
Virtual tests conducted on the basis of the finite element method (FEM) using the LS-Dyna multi-purpose software complex [9-12]. As a result of the virtual experiment, a graph of the force dependence on the displacement of the compressing plate plotted, which compared with the identical graph obtained during the full-scale experiment (figure 9). The process of compressing the energy absorbing element sample from the UHMWPE shown in figure 10.
Figure 9. Graph of forces dependence on compressive element movements.

Figure 10. Compression process of FE model of energy absorbing element sample from UHMWPE.

Based on the results of the virtual experiment, the energy absorption of the sample from the UHMWPE was $U=0.335 \text{ kJ}$.

Consider one of the possible design options for sections of energy absorbing elements in the form of cylinders from UHMWPE (figure 11). To compare energy absorption capacity, a model of energy absorption elements in the form of metal sections of honeycombs also constructed (figure 12).
Figure 11. Possible design of UHMWPE cylinders assembled.

Figure 12. Model of steel energy absorbing elements (honeycombs).

To determine the amount of energy absorption capacity, a virtual model of compression tests of energy absorption elements assembled built. The test diagram shown in figure 13. The loading process realized by means of an absolutely rigid plate moving at a speed of 20 mm·min$^{-1}$.

![Virtual test schematic diagram](V=20\text{ mm}\cdot\text{min}^{-1})

(a) steel energy absorbing elements, (b) UHMWPE cylinders.

4. Results

Based on the results of virtual tests, energy absorption capacity values obtained. The energy absorption diagrams shown in figure 14.

Table 1 shows the range of energy absorption values of sections from UHMWPE at an external diameter of 90 mm during loading, and the weight of the structure. For comparison, table 2 shows similar values for steel elements.
Figure 14. Energy absorption diagrams.

Table 1. Energy absorption and mass of structure from UHMWPE.

| Parameter          | Thickness 8 mm | Thickness 9 mm | Thickness 10 mm | Thickness 11 mm |
|--------------------|----------------|----------------|-----------------|-----------------|
| Energy absorption  | $6 \cdot 10^7$ J | $6.42 \cdot 10^7$ J | $7.73 \cdot 10^7$ J | $9.24 \cdot 10^7$ J |
| Weight             | 37.99 kg       | 42.49 kg       | 46.92 kg        | 51.32 kg        |

Table 2. Energy absorption and mass of structure from steel.

| Parameter                        | Weight | Energy absorption |
|----------------------------------|--------|-------------------|
| Steel honeycomb with 2 mm wall thickness | 64.72 kg | $6.52 \cdot 10^7$ J |

5. Conclusions

Based on the results obtained, it can previously concluded that the UHMWPE can used as a material for energy absorbing elements of the safety modular absorber. With an outer diameter of 90 mm and thicknesses of 8 mm to 11 mm, energy absorption closest to steel achieved.

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