MACHINE BUILDING

Original article
UDC 331.45
https://doi.org/10.23947/2541-9129-2022-2-49-68

Research on the effectiveness of aluminum passive safety elements in cars based on computer simulation

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Introduction. The research of energy-absorbing element made of aluminum alloy, which is part of the passive safety system of a racing car, is carried out in the article. Designing and testing of the energy absorbing element was performed within the framework of the technical regulations of the international student engineering competition Formula SAE. Formula SAE is an engineering competition of student teams organized by the Society of Automotive Engineers (SAE).

The design and analysis of the dynamic performance of the research object were performed in the computer-aided design system (CAD) ANSYS® Workbench SpaceClaim and ANSYS Explicit Dynamics.

Problem Statement. The task of this research is to analyze the effectiveness of the use of aluminum alloy as the main material for the manufacture of the energy-absorbing element of the passive safety system of the car.

Theoretical Part. Eleven structures of different shapes (structures) made of aluminum alloy 6063 were developed as promising models of energy-absorbing elements. A simulation crash test (frontal impact) was carried out, as a result of which it was possible to study the flow of deformation in the structure, to find the main zones of stress and load. This study of energy-absorbing elements can be used to justify the choice of material for the manufacture of passive car safety elements by car manufacturers and machine builders.

Conclusions. The result of the research is a simulated process of destruction (or deformation) of the energy-absorbing element responsible for the absorption of energy in case of a frontal impact. The dependence of the manufacturing material and the shape of the energy absorbing element on the qualitative and quantitative characteristics of the passive car safety system has been investigated. Loads and stresses appearing in the structure of energy absorbing element have been studied. The efficiency of using aluminum alloy in promising car passive safety elements has been proved. Simulations of crash-tests showed that the use of progressive materials of construction elements of passive safety of vehicles, namely, aluminum alloys in an optimized (as a result of modeling) performance allows you to achieve high levels of protection of the pilot and passengers of the vehicle.

The analysis of the absorbed energy value distribution allows revealing the direction for further improvement of the car passive safety systems. The influence of energy absorbing element manufacturing material on the processes occurring during frontal impact has been established. A universal technology of crash-testing (modeling of impact processes) of an energy absorbing element with a rigid obstacle has been developed in Ansys software. The percentage ratio (redistribution) of energy absorbed by frontal elements of passive safety of the car has been investigated.

Keywords: energy absorbing element, aluminum alloy, deformation, efficiency, crash test, vehicle passive safety system.

For citation: Zhukov L. A., Kuzminov A. L. Research on the effectiveness of aluminum passive safety elements in cars based on computer simulation. Safety of Technogenic and Natural Systems. 2022;2:49−68. https://doi.org/10.23947/2541-9129-2022-2-49-68

Introduction. The car is the most common land transport in the world as of 2022. Thus, in the Russian Federation, road transport occupies 61.6% of the total volume of passenger traffic (Fig. 1) [1].

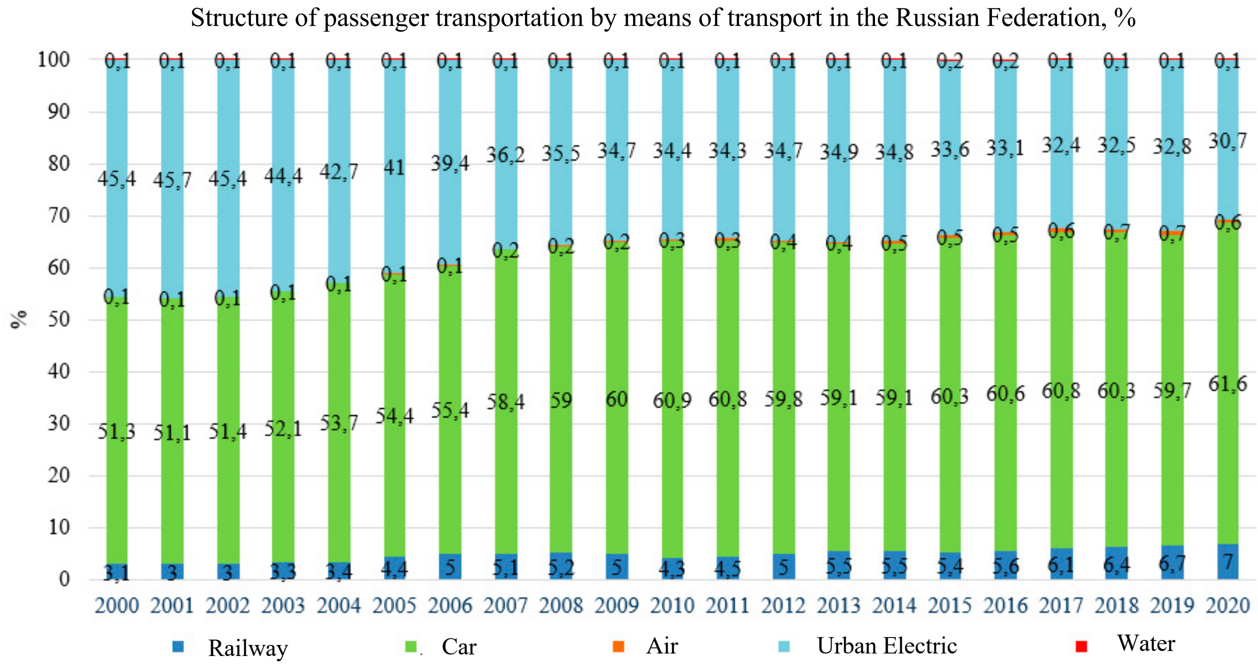


Fig. 1. Structure of passenger transportation by means of transport in the Russian Federation (in percentage terms from 2000 to 2020)

The main structural material in mechanical engineering is steel. However, with the development of technology in the automotive industry, new priority areas of development have emerged: reduction of fuel consumption, reduction of CO_2 emissions, improvement of vehicle safety, use of a fully electric or hybrid power sections in the car [2]. A tool for solving priority tasks in the machine-building industry is the use of aluminum alloys in the construction of a car [3]. As of 2021, aluminum consumption in mechanical engineering accounted for more than 10% of the total aluminum production in the world. The key factors of the increased demand for aluminum in mechanical engineering is an increase in the production of cars, as well as the number of their components and assemblies made of aluminum. Thus, the share of aluminum in the total weight of the car has grown from an average of 35 (1970s) to 152 kilograms (2021), and by 2025 the share of aluminum may reach 270 kilograms [4].

Use of aluminum in the automotive industry allows us to achieve the following results: reduce the weight of the car, increase the load capacity, reduce fuel consumption (and, as a result, carbon dioxide emissions), improve acceleration and braking dynamics, increase vehicle safety, since aluminum has better energy absorption characteristics than steel.

The ability of aluminum alloys to absorb shocks is 2-3 times higher than that of steel, and this has accelerated their introduction into the automotive industry. For example, in Tesla cars, a three-level passive car safety system made of aluminum alloys is installed. The first level of protection is an aluminum bump on the bottom of the Tesla Model S, made in the form of a hollow aluminum bar of a special shape, which throws objects lying on the road that have fallen under the car up, directing the main blow to the area of the front trunk, thereby protecting the battery compartment and maintaining the controllability of the car. The second level of protection is an eight-millimeter impenetrable plate made of aluminum-titanium alloy, which protects the battery compartment from damage. The third level of protection is a shield made of die-cast aluminum, which dissipates the impact energy and, if the obstacle is solid and stationary, lifts the car above it [5].

The use of aluminum as the main material in the manufacture of the car body became widespread in 2021. This is due to the fact that deformations in aluminum structures are localized in compact zones, preventing other parts of the body from deforming, thereby maintaining maximum safety of the part of the car where the passengers are. A promising direction for car manufacturers is also the creation of closed-cycle production facilities in which scrap aluminum parts of recycled cars will serve as raw materials for the manufacture of spare parts for new vehicles.

The relevance of research in the field of passive vehicle safety is due to the complexity and insufficient knowledge of testing methods and virtual simulation of dynamic crash tests of passive vehicle safety elements.

It is the passive car safety systems made of aluminum that have become the subject of research, the results of which are presented in this article.

Problem Statement. The initial objective of the study was to analyze the effectiveness of the use of aluminum in the car passive safety elements.

As an instrumental research method, modeling of the passive safety device of a racing car — an energy-absorbing element made of aluminum alloy and its further testing for energy-absorbing properties during frontal impact was used (Fig. 2) [6].

Fig. 2. Design of a racing car designed according to the FSAE regulations, with an energy-absorbing element (indicated in green)

As initial data for solid-state computer modeling and energy-absorbing element research, technical requirements for the research object from the technical regulations of the Formula SAE project were adopted.

The requirements of the FSAE technical regulations:

— according to paragraph T2.18.2, the energy-absorbing element must be installed in front of the front partition of the car frame, have dimensions of at least 100 mm in height and 200 mm in width at a distance of at least 200 mm from the front partition along the axis of the frame, securely fixed to the front partition (using glue, welding or bolted connection);

— according to paragraph T2.18.3, a protective plate made of aluminum with a thickness of 4 mm or of structural steel with a thickness of 1.5 mm must be integrated on all vehicles;

— according to paragraph T2.20.1, the energy-absorbing element is tested using a hard frontal impact (at an angle of 90 degrees) at a vehicle speed of 7 m/s. As a result of the energy-absorbing element tests, the total amount of absorbed energy should be at least 7,350 J, and the maximum overload should not exceed 40 g [7].

The results of the study can be applied by machine-building enterprises when choosing and justifying the effectiveness of using aluminum as the main material for passive car safety elements.

Theoretical Part. To solve this problem, aluminum alloy 6063 (AW-6063) was chosen as the material for manufacturing the energy-absorbing element, the chemical composition of which is presented in Table 1 [8].

Table 1

Chemical composition of aluminum 6063

Chemical composition of alloy 6063 according to EN 573-3 standards									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other elements	
0.2–0.6	0.35	0.1	0.1	0.45–0.9	0.1	0.1	0.1	0.05	0.15

Aluminum 6063 is an aluminum alloy with magnesium and silicon as alloying elements. The standard of its composition control is supported by the Aluminum Association. It usually has good mechanical properties, is amenable to heat treatment and welding. Aluminum 6063 is the most common alloy used for the manufacture of profiles with a fixed cross-section (extrusion) of aluminum. It allows you to form complex shapes with very smooth surfaces suitable for anodizing. Aluminum 6063 is an aluminum alloy of increased ductility and corrosion resistance. The corrosion resistance of this alloy is high: it is not prone to stress corrosion cracking, regardless of the condition of the material. It is suitable for automated assembly operations because it is well welded by arc welding in an inert gas environment.

Table 2 provides the mechanical properties of aluminum 6063.

Table 2

Mechanical properties of aluminum 6063

Specific gravity	2690 kg/m^3 (2.69 g/cm^3 at 20° C)
Tensile strength (temporary tear resistance), min., Rm, MPa	240
Yield strength, min., Rp0,2 в N/mm^2	215
Elongation, min., %	11
Brinell hardness, HB max.	78
Tensile modulus of elasticity, MPa	68300
Shear modulus of elasticity, MPa	25800
Compressive modulus of elasticity, MPa	69700
Coefficient of thermal expansion, µm/m–C	23.4
Poisson's ratio	0.33

Figure 3 provides the arrangement of aluminum 6063 in the grid of other aluminum alloys depending on the percentage of Si (silicon) and Mg (magnesium).

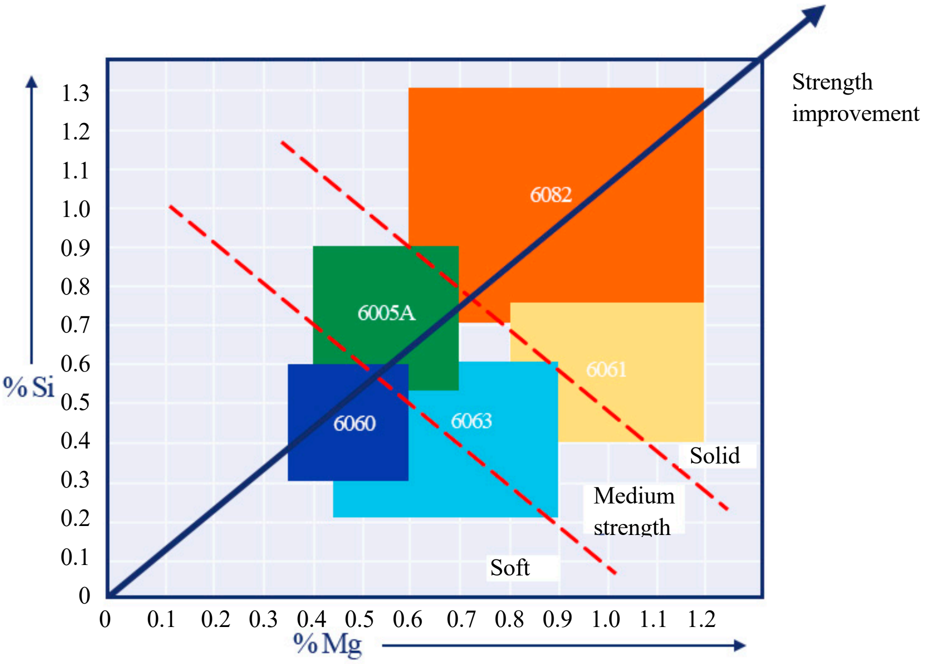


Fig. 3. Grid arrangement of aluminum alloys depending on the percentage of silicon and magnesium

Thus, we can draw a preliminary conclusion that aluminum alloy 6063 has mechanical properties that allow it to be used in passive safety elements production that require sufficient strength from the material and the ability to control deformation under calculated loads.

The Ansys SpaceClaim (CAD) software was used to model the structures of energy-absorbing elements. The shape and structural arrangement of the energy-absorbing element were chosen based on the capacity of the energy-absorbing device for structural deformation of the aluminum alloy during the manufacture of the energy-absorbing element.

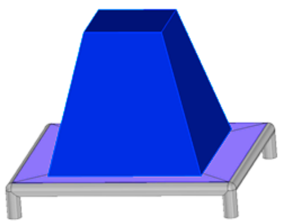
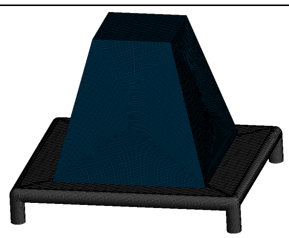
As promising models of energy-absorbing elements made of aluminum, the models of structures were developed, which are presented in Table 3. The Automatic method in Ansys Explicit Dynamics with a set element size of 2 mm was chosen as a method for constructing a finite-difference grid [9].

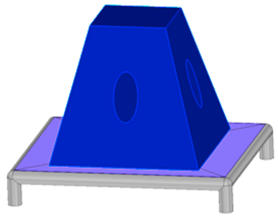
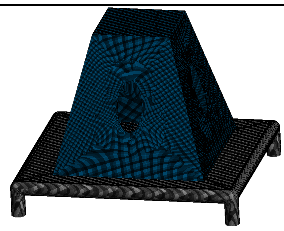
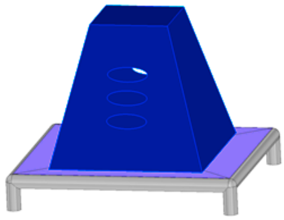
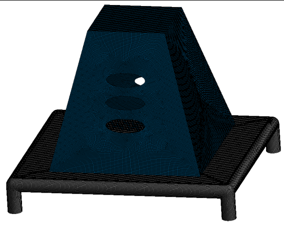
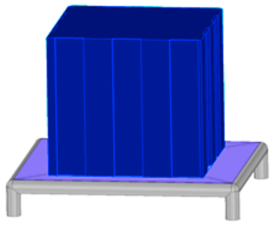
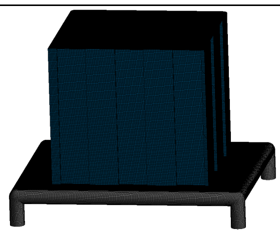
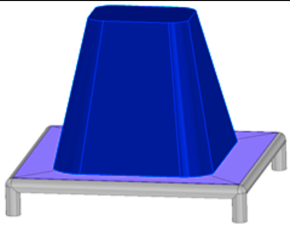
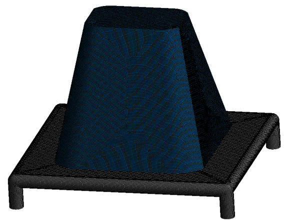
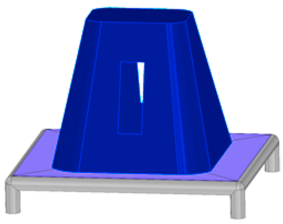
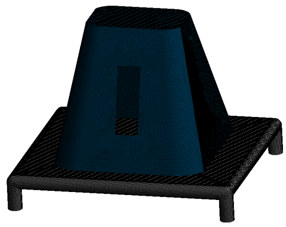
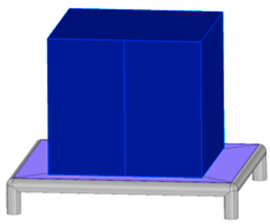
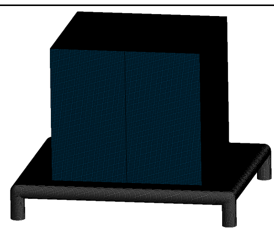
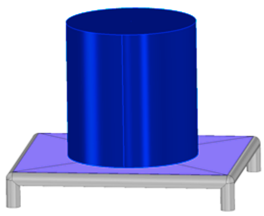
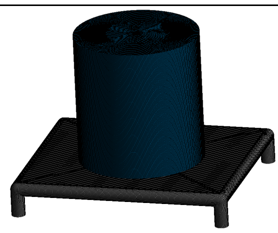
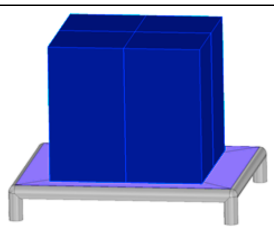
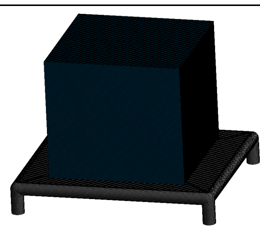
The choice of the size of the grid elements is due to the design of the model of energy-absorbing elements, as well as the ability to conduct an accurate study of the distribution of loads in the energy-absorbing elements at the time of collision [10].

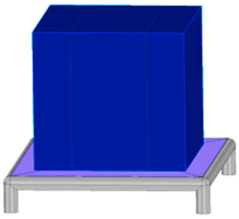
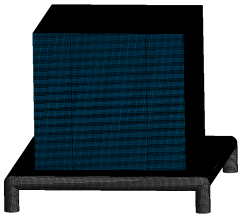
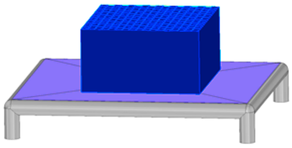
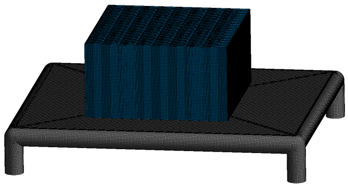
The number of nodes and grid elements of the developed models of energy-absorbing elements is also presented in Table 3.

Table 3

Promising models of energy-absorbing elements made of aluminum 6063 and their finite element grid

No	Structural Name	3D model	Finite Element Grid	Grid Characteristic
1	Energy absorbing element in the form of a truncated pyramid			Statistics Nodes 145685 Elements 145167

No	Structural Name	3D model	Finite Element Grid	Grid Characteristic
2	Energy-absorbing element in the form of a truncated pyramid with four manufacturing holes			Statistics Nodes 142751 Elements 142056
3	Energy-absorbing element in the form of a truncated pyramid with six manufacturing holes			Statistics Nodes 143989 Elements 143265
4	Rectangular energy absorbing element made of aluminum shape			Statistics Nodes 186165 Elements 185276
5	Energy absorbing element in the form of a smoothed truncated pyramid			Statistics Nodes 141020 Elements 140456
6	Energy absorbing element in the form of a smoothed truncated pyramid with two manufacturing rectangular holes			Statistics Nodes 138789 Elements 138065
7	Two-section energy-absorbing element			Statistics Nodes 185729 Elements 184826
8	Energy absorbing element of cylindrical shape			Statistics Nodes 149332 Elements 149022
9	Energy-absorbing element of a four-section design			Statistics Nodes 211941 Elements 211065

No	Structural Name	3D model	Finite Element Grid	Grid Characteristic
10	Energy-absorbing element of a three-section design			**Statistics** Nodes 212056 Elements 211035
11	Energy absorbing element made of aluminum honeycomb			**Statistics** Nodes 465640 Elements 366902

In the process of research, development and calculations of energy-absorbing elements, it is necessary to take into account the fact that the finite element method (FEM) is an approximate method, the accuracy of which depends on assumptions related to the type of element and the size of the grid. In the structural elements of an energy-absorbing element, where stress and strain changes occur by an order of magnitude or more, a denser grid is required. In elements subject to almost constant stress, with a minimal difference in values, as well as in elements that do not require accurate research, a rare grid with a large element size is used. When forming a finite element grid (FE), both triangular and rectangular elements can be used simultaneously, while the grid is constructed without gaps between the elements (Fig. 4).

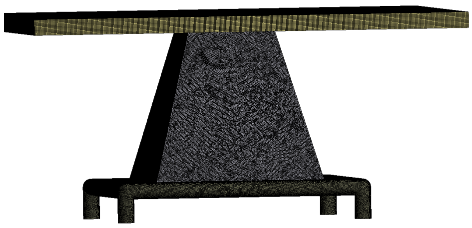


Fig. 4. Example of the grid of the FE model of an energy-absorbing element and a rigid obstacle

The dynamic study (crash test) was carried out using the Ansys Workbench software with the Explicit Dynamics dynamic analysis software package installed (Fig. 5).

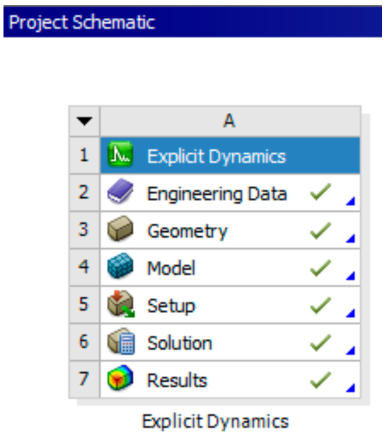


Fig. 5. Structure of the Ansys Dynamic Research project

The dynamic research project consists of the following main elements (stages):

− Engineering Data — a database of materials in which you can both select and configure ready-made materials, and add your own;

− Geometry — an environment for the development of models, structures, surfaces, allows you to upload a ready-made model to a project or develop it from scratch;

− Model — a system that combines geometry, selected materials, coordinate system, connections in the assembly, the grid of the FE model and the settings for conducting research (Setup). This section allows you to select the area of dynamic research and immediately display the results in graphically interactive form after the calculations are completed;

− Solution — calculations are included in the Model subsection, can be extrapolated to other analysis systems;

− Results — the results of calculations performed on the studied indicators (deformations, stresses, changes in speed, displacement, etc.).

All data on the material are entered in the Engineering Data section (Fig. 6).

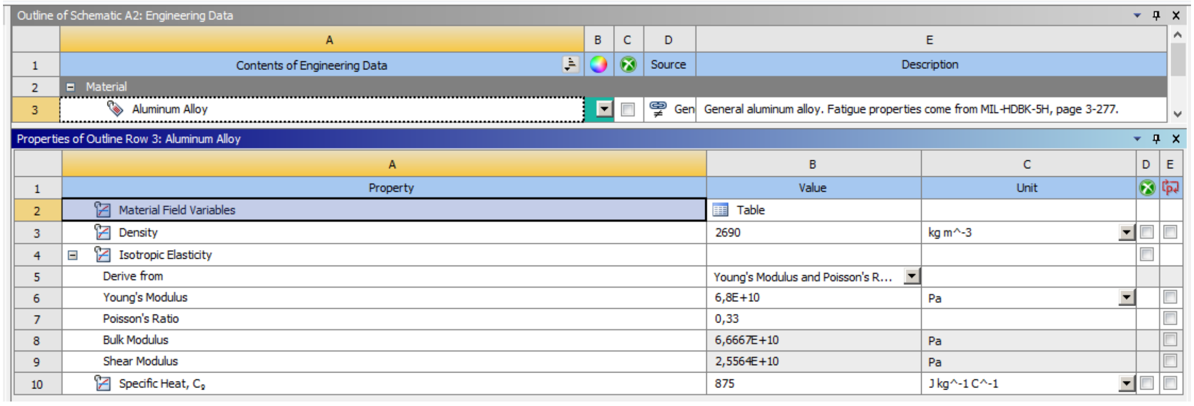


Fig. 6. The card of the aluminum alloy 6063 (AW-6063) material in Ansys Engineering Data

The speed of calculation by the software and the requirements for the developer's equipment depend on the choice of the design method. The model of the energy-absorbing element should be located close to the virtual obstacle (at an angle of 90 degrees), this allows for timely receipt of the necessary information and data on the processes occurring during the collision during the calculation (Fig. 7).

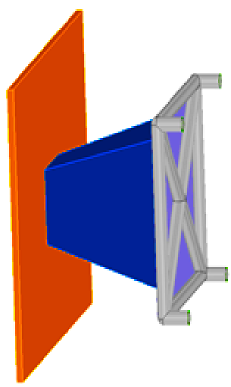
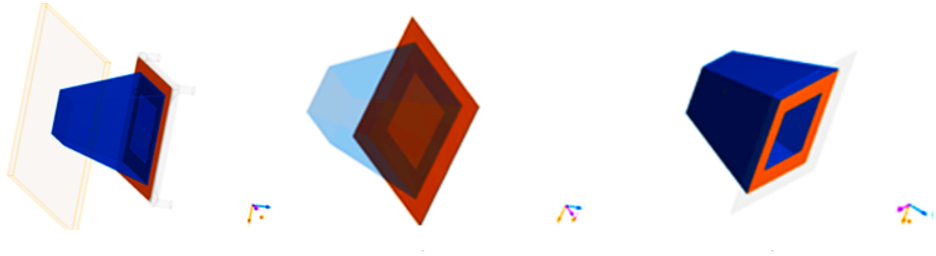


Fig. 7. An example of the location of an energy-absorbing element in front of a rigid obstacle

After installing materials for all components of the assembly, the connections (contacts) between the assembly nodes are configured (Fig. 8). The contacts of the components are configured in the Connection subsection. Thus, a prerequisite for a correct study is the absence of a connection (contact) of an energy-absorbing element with an obstacle, since these objects are not connected in real conditions. During the study, the following connections (contacts) of the components were established:

− car frame — front platform;

− front platform — energy-absorbing element.



a) *b*) *c*)

Fig. 8. An example of installing contacts between an energy-absorbing element and a front platform mounted on a car frame: a) general view of contacts in the design model of energy-absorbing elements; b) contact between the car frame and the front platform; c) contact between the energy-absorbing element and the front platform

After creating a grid and installing contacts in the assembly, restrictions are formed in the model and the speed of movement of the assembly of the front part of the car is set (Fig. 9). During modeling, the contour and the rear wall of the obstacle are fixed, and restrictions are introduced in the displacement of the car frame. The impact velocity of the energy-absorbing element on a rigid obstacle is assumed to be 7 m/s, according to the Formula SAE technical regulations (Fixed Support, Displacement, Velocity functions are used for these operations).

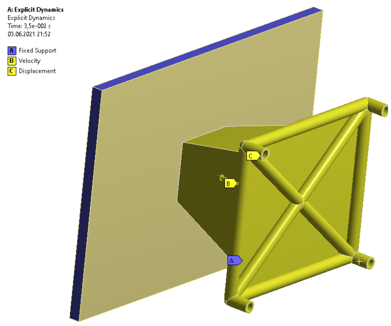
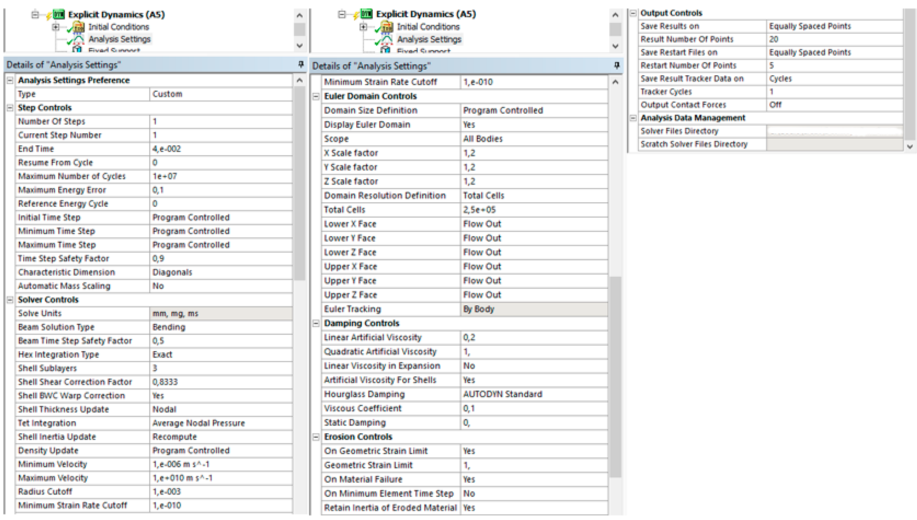


Fig. 9. Adjustment of movements of the test sample of the energy absorbing element for the crash test

At the last technological stage, the parameters of the dynamic test are configured using the Analysis Setting module; and the necessary indicators for calculation are selected (Fig. 10).



Explicit Dynamics (A5)

Details of "Analysis Settings"

Analysis Settings Preference	
Type	Custom
Step Controls	
Number Of Steps	1
Current Step Number	1
End Time	4,e-002
Resume From Cycle	0
Maximum Number of Cycles	1e+07
Maximum Energy Error	0,1
Reference Energy Cycle	0
Initial Time Step	Program Controlled
Minimum Time Step	Program Controlled
Maximum Time Step	Program Controlled
Time Step Safety Factor	0,9
Characteristic Dimension	Diagonals
Automatic Mass Scaling	No
Solver Controls	
Solve Units	mm, mg, ms
Beam Solution Type	Bending
Beam Time Step Safety Factor	0,5
Hex Integration Type	Exact
Shell Sublayers	3
Shell Shear Correction Factor	0,8333
Shell BWC Warp Correction	Yes
Shell Thickness Update	Nodal
Tet Integration	Average Nodal Pressure
Shell Inertia Update	Recompute
Density Update	Program Controlled
Minimum Velocity	1,e-006 m s^-1
Maximum Velocity	1,e+010 m s^-1
Radius Cutoff	1,e-003
Minimum Strain Rate Cutoff	1,e-010

Explicit Dynamics (A5)

Details of "Analysis Settings"

Minimum Strain Rate Cutoff	1,e-010
Euler Domain Controls	
Domain Size Definition	Program Controlled
Display Euler Domain	Yes
Scope	All Bodies
X Scale factor	1,2
Y Scale factor	1,2
Z Scale factor	1,2
Domain Resolution Definition	Total Cells
Total Cells	2,5e+05
Lower X Face	Flow Out
Lower Y Face	Flow Out
Lower Z Face	Flow Out
Upper X Face	Flow Out
Upper Y Face	Flow Out
Upper Z Face	Flow Out
Euler Tracking	By Body
Damping Controls	
Linear Artificial Viscosity	0,2
Quadratic Artificial Viscosity	1,
Linear Viscosity in Expansion	No
Artificial Viscosity For Shells	Yes
Hourglass Damping	AUTODYN Standard
Viscous Coefficient	0,1
Static Damping	0,
Erosion Controls	
On Geometric Strain Limit	Yes
Geometric Strain Limit	1,
On Material Failure	Yes
On Minimum Element Time Step	No
Retain Inertia of Eroded Material	Yes

Output Controls	
Save Results on	Equally Spaced Points
Result Number Of Points	20
Save Restart Files on	Equally Spaced Points
Restart Number Of Points	5
Save Result Tracker Data on	Cycles
Tracker Cycles	1
Output Contact Forces	Off
Analysis Data Management	
Solver Files Directory	
Scratch Solver Files Directory	

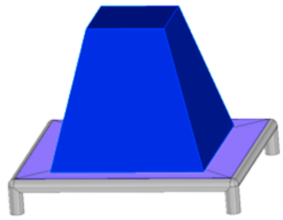
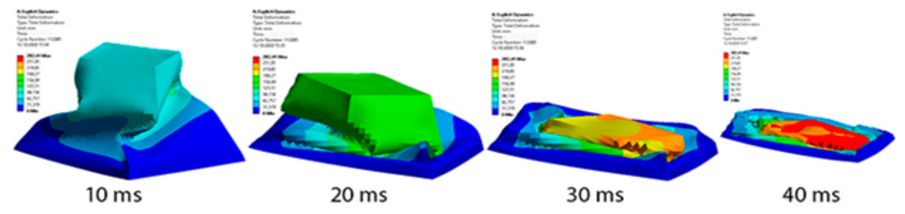
Fig. 10. Setting the parameters of the Analysis Setting dynamic test

In the settings, it is recommended to set the End Time to no more than 50 ms (0.05 s), since on average, in 40 milliseconds, the impact is completely absorbed and the subsequent rebound of the car occurs. With a simulation time of 40 milliseconds, an average of 126,000-150,000 calculation operations-cycles are performed.

In order to find the most promising structural solutions for energy-absorbing aluminum alloy elements and their further analysis, crash tests were conducted with readings in the range from 0 to 40 milliseconds. Table 4T provides the results of the tests.

Table 4

Deformations of energy-absorbing elements at four time points after the impact (10-20-30-40 milliseconds)

<table>
<tr><th>№</th><th>3D Model</th><th>Deformation of the energy-absorbing element</th></tr>
<tr><td>1</td><td></td><td>
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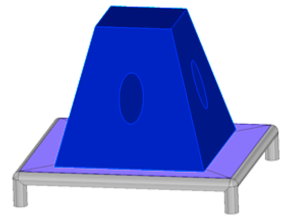
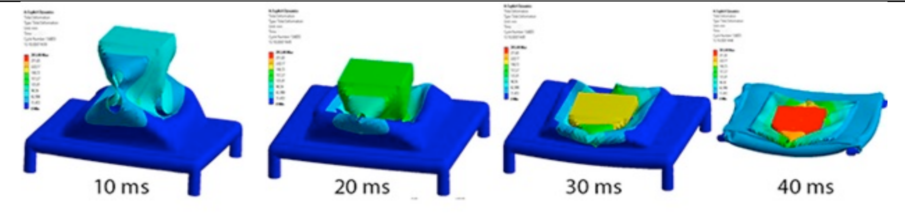
<tr><td>2</td><td></td><td>
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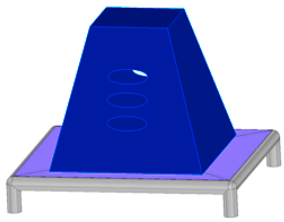
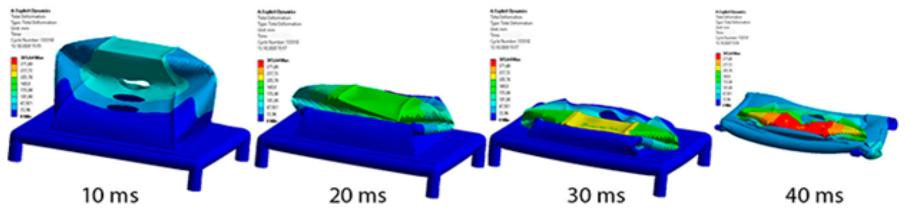
<tr><td>3</td><td></td><td>
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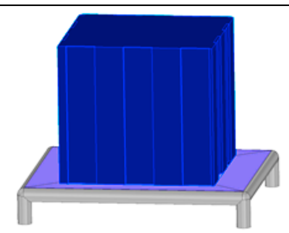
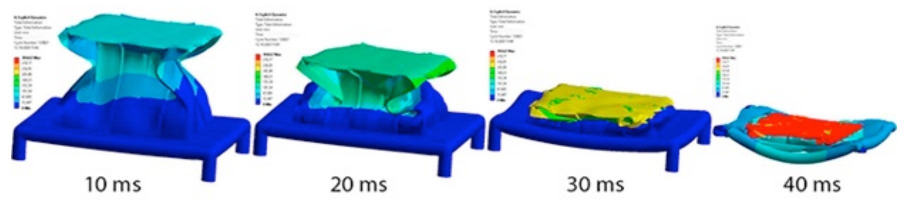
<tr><td>4</td><td></td><td>
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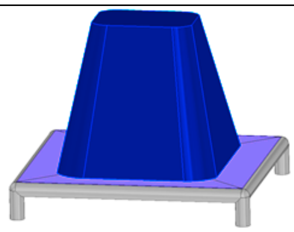
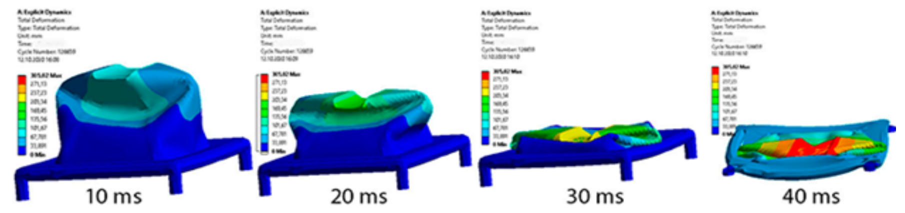
<tr><td>5</td><td></td><td>
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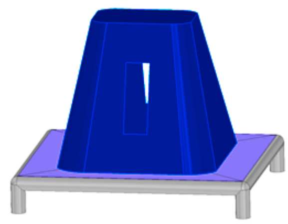
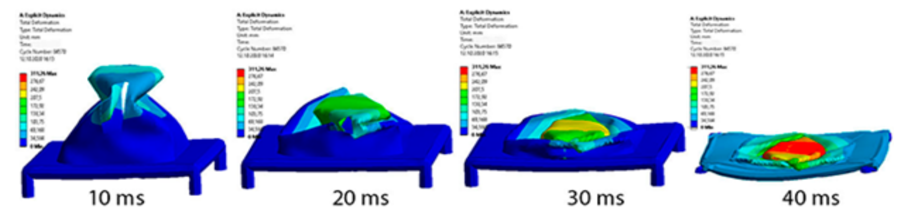
<tr><td>6</td><td></td><td>
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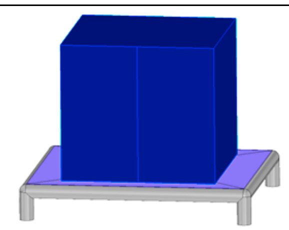
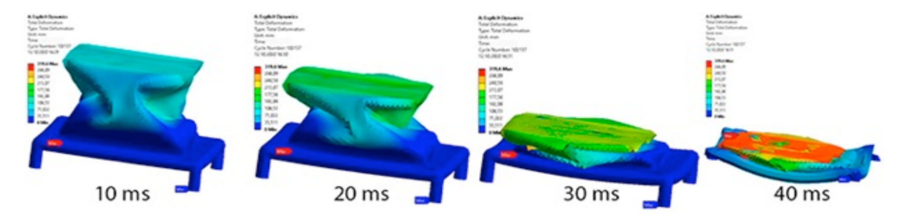
<tr><td>7</td><td></td><td>
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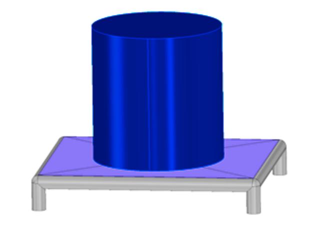
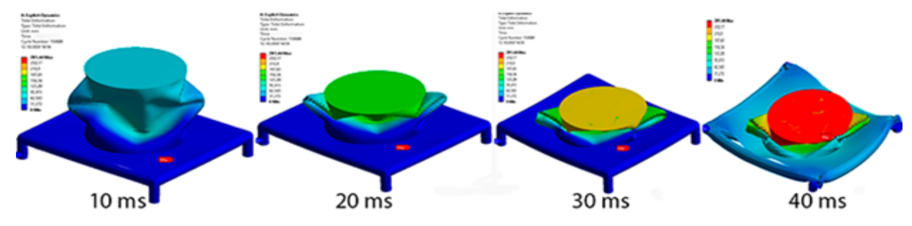
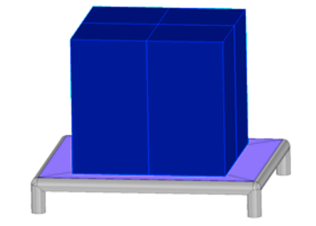
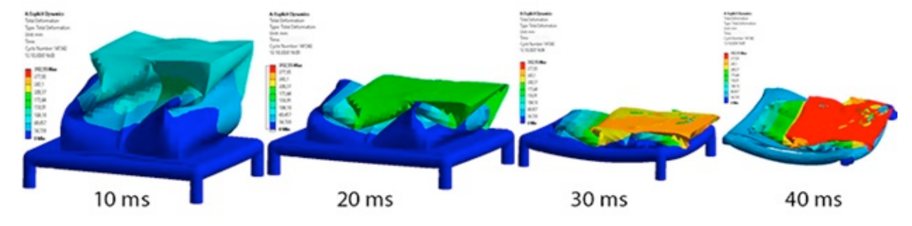
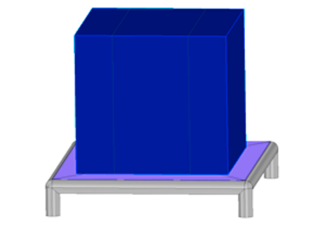
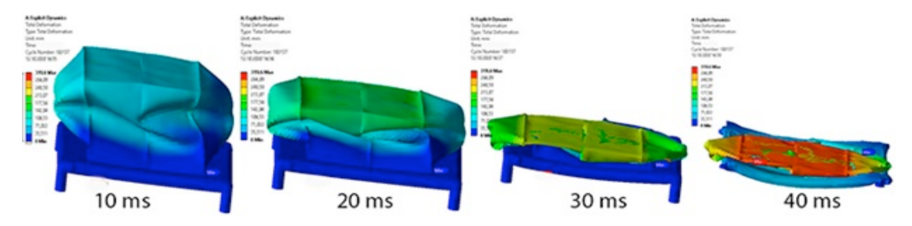
№	3D Model	Deformation of the energy-absorbing element
8		
9		
10		

Based on the results of computer modeling for further analysis and selection of promising designs of energy-absorbing elements, summary graphs of deformation and effectively absorbed energy were formed (Fig. 11, 12).

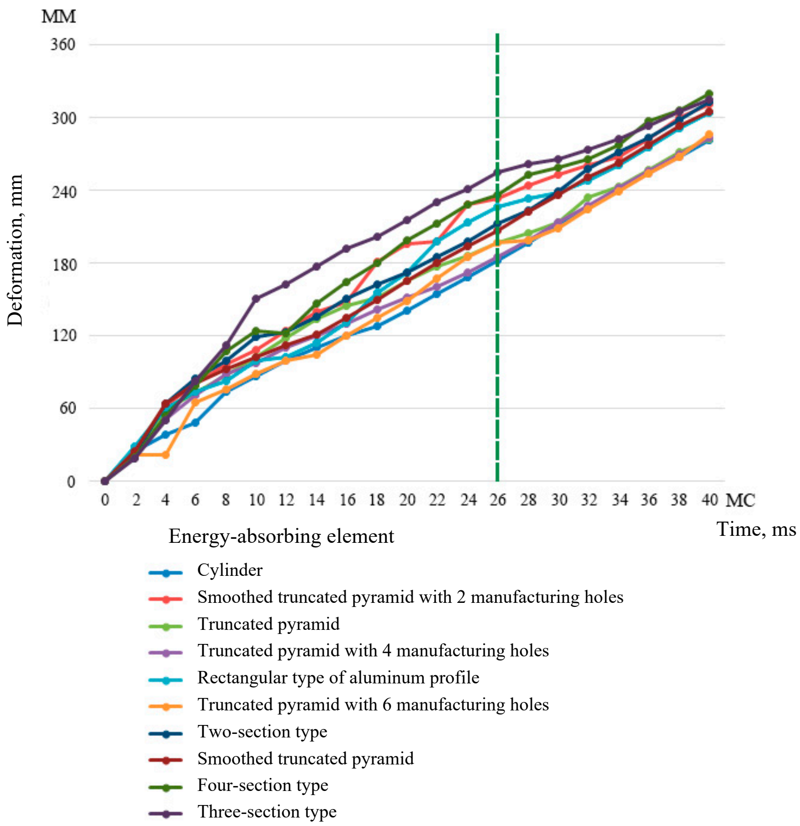


Fig. 11. Diagram of deformation of energy-absorbing elements in the time range of 0-40 milliseconds

The green line in Figure 11 limits the zone from 0 to 26 milliseconds. During this time range, the most effective deformation (Effective Plastic Strain) of the energy-absorbing element occurred, during which it did not deform or experienced minor displacements of the space frame of the car.

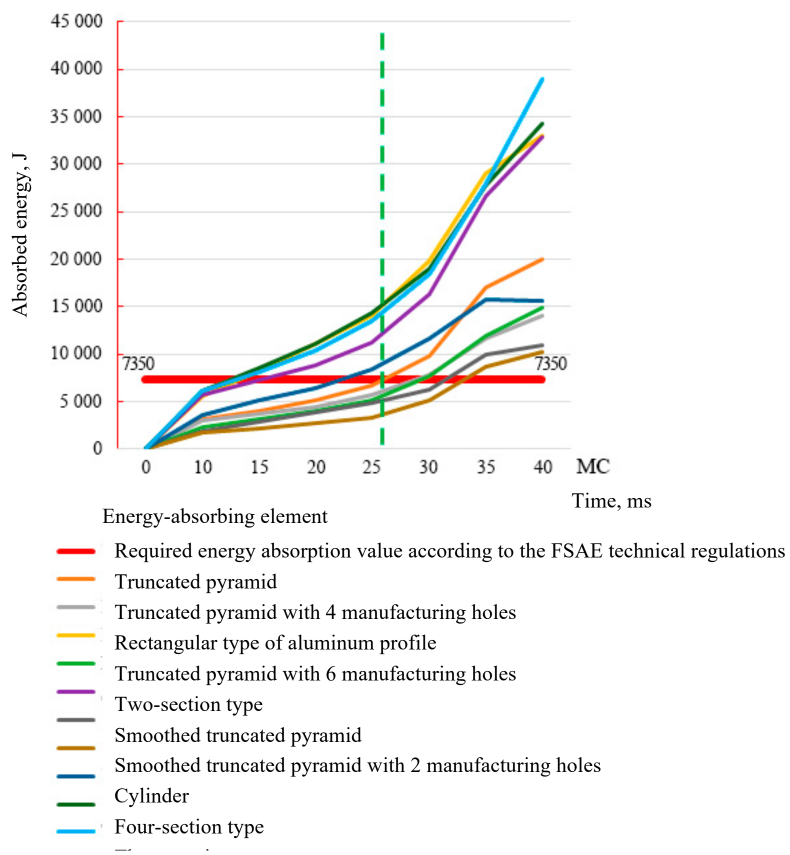
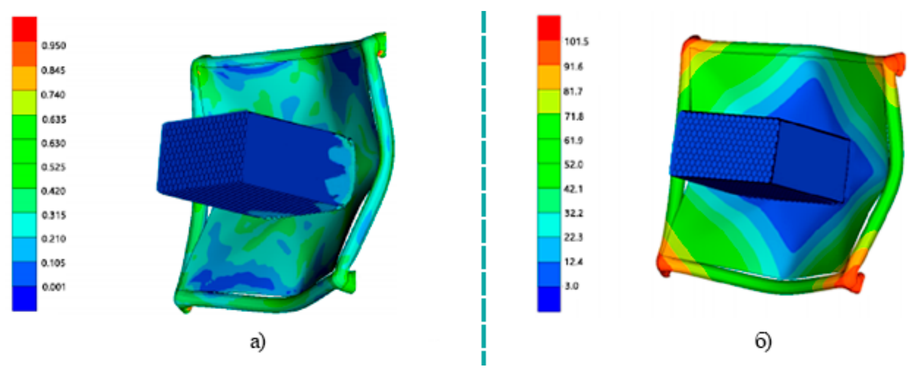


Fig. 12. Diagram of absorbed energy (J) by energy-absorbing elements in the time range of 0-40 milliseconds

The green line in Figure 12 also limits the zone from 0 to 26 milliseconds. In this time range, the energy-absorbing element absorbed the incoming energy by its own deformation without serious damage to the remaining elements of the car. The upper value of this time range (26 milliseconds) is the time during which an aluminum alloy energy-absorbing element is able to effectively absorb a shock, with a properly calculated design, this happens without significant overloads.

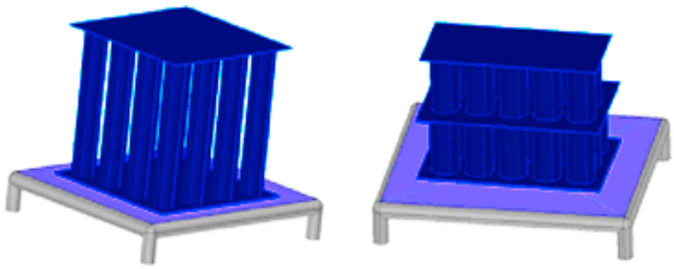
The calculation results showed that the design of the energy-absorbing element made of aluminum honeycomb does not meet the safety requirements of the Formula SAE technical regulations. The rigidity of this design turned out to be too large, which caused premature deformation of the front plate and frame of the car, and the resulting overloads > 20 g do not allow the use of this passive safety element in the Formula SAE car (Fig. 13).



a) b)

Fig. 13. Stresses and deformations in an energy-absorbing element made of aluminum honeycomb: a) stresses in an energy-absorbing element made of aluminum honeycomb (hPa); b) deformation in an energy-absorbing element made of aluminum honeycomb (mm)

Additionally, energy-absorbing multi-component elements with cylindrical structures were investigated, but they turned out to be absolutely ineffective (Fig. 14). The high rigidity of the structure did not allow absorbing the impact in sufficient quantity due to the deformation of the energy-absorbing element, therefore, the use of these structures in a car made according to the Formula SAE regulations is out of the question.



a) *b*)

Fig. 14. Multi-component energy-absorbing elements: a) a single-level energy-absorbing element with 16 cylinders; b) a two-level energy-absorbing element with 15 cylinders on the first and 10 cylinders on the second level

For further analysis of the problem, a gradation of energy-absorbing elements is made according to their efficiency, which is built on aggregate qualities (Fig. 15). They include the ability to absorb a sufficient amount of incoming energy, to absorb the impact without exceeding the permissible overload indicators, the ability to deform without premature destruction or displacement of the energy-absorbing element.

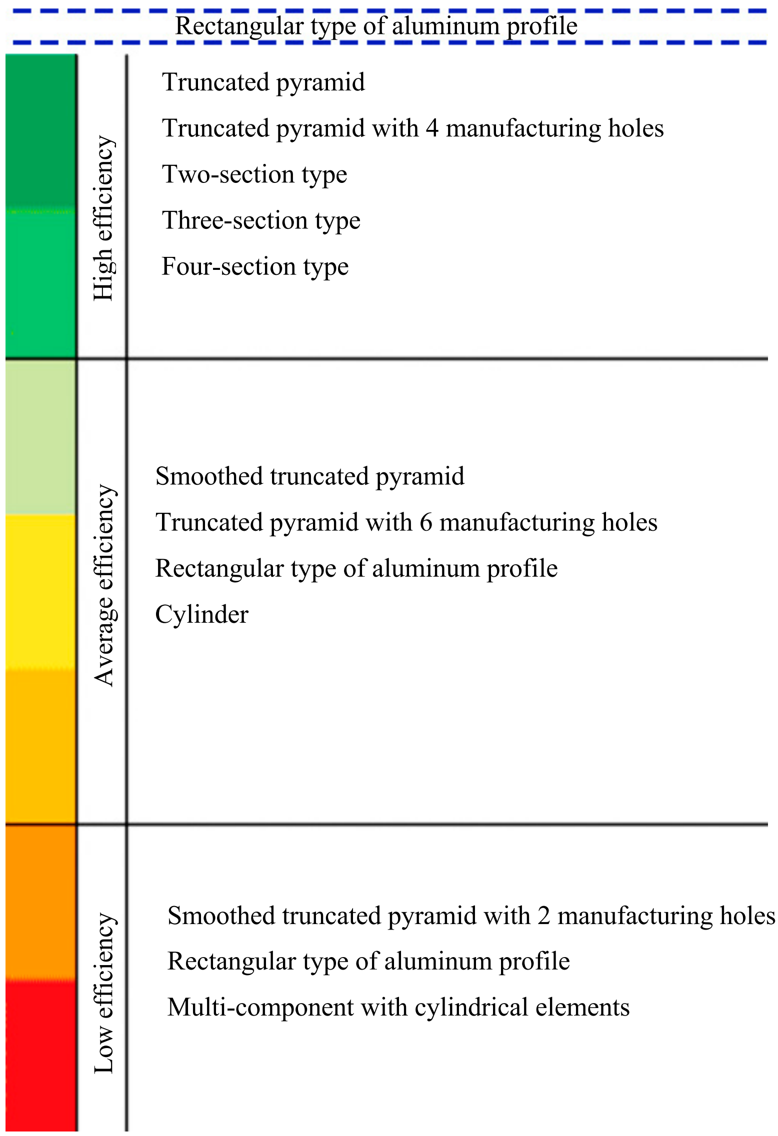


Fig. 15. Gradation of energy-absorbing elements by efficiency

Further research was carried out only for energy-absorbing elements of the "high efficiency" category. The data for the graphs were formed from a control point located at the center of the intersection of the front pipes of the space safety frame of the car (Fig. 1 6).

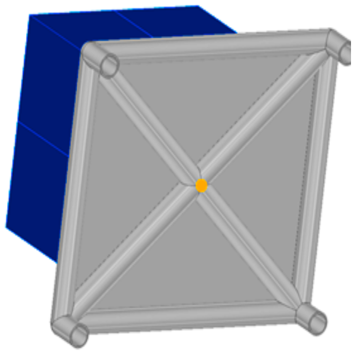


Fig. 16. The control point (indicated in yellow) on the structure of the energy-absorbing element

Figures 17 and 18 show the graphs of movement, speed and acceleration for the control point of effective design options for energy-absorbing elements.

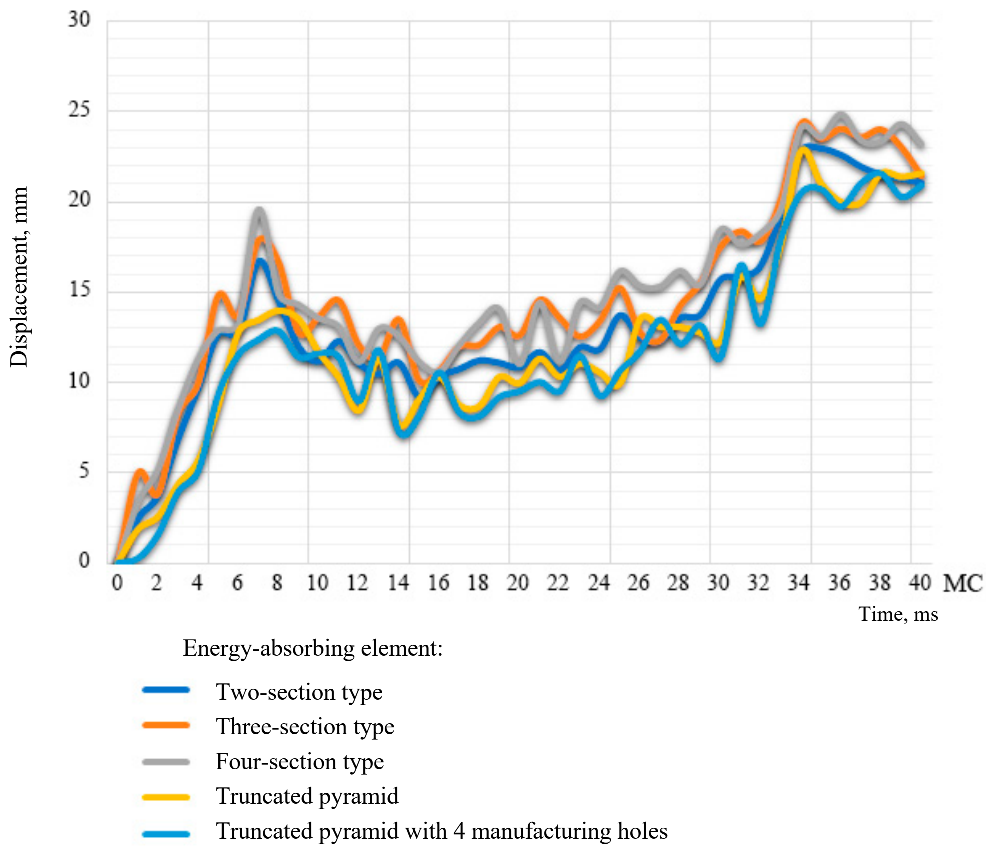


Fig. 17. Graph of the dependence of the movement of the energy-absorbing structure on time (the results are obtained from the control point in Fig. 16)

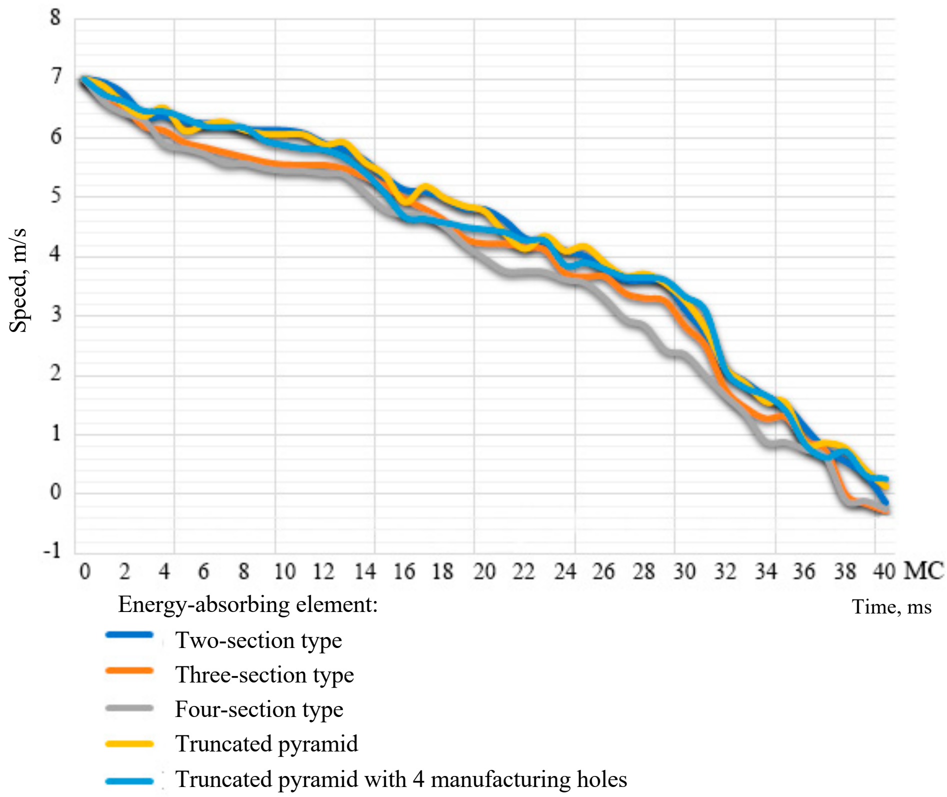


Fig. 18. Graph of the dependence of the deceleration rate of the energy-absorbing structure on time (the results are obtained from the control point in Fig. 16)

During the simulation, the main stress concentration zones were identified (Fig. 19). Thus, it was found that the intersection (center) of the diagonal pipes of the space frame, the corner elements of the frontal part of the car frame, the perimeter of the plate to which the energy-absorbing element is attached, in places of structural bends and fasteners of the energy-absorbing element, are subjected to the main loads.

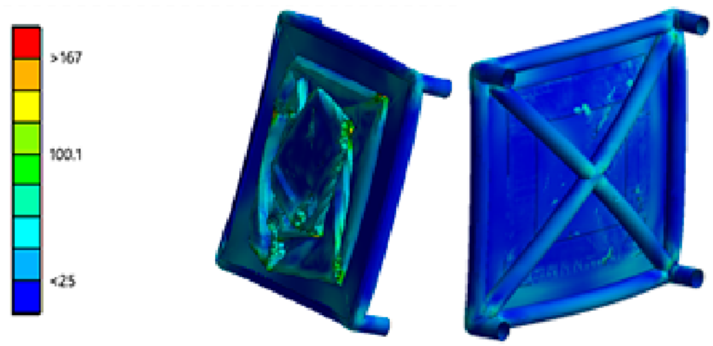


Fig. 19. Places of intense concentration of accumulated stresses (hPa)

Based on computer simulation, it can be concluded that all the presented energy-absorbing elements from the "high efficiency" category can be used as a passive safety system of a racing car. The category of effective energy-absorbing elements has a well-predicted deformation in case of a frontal impact. Additionally, several structures were tested with a frontal impact with 40% overlap, which is considered the most difficult testing of the existing safety elements (Fig. 20) [11].

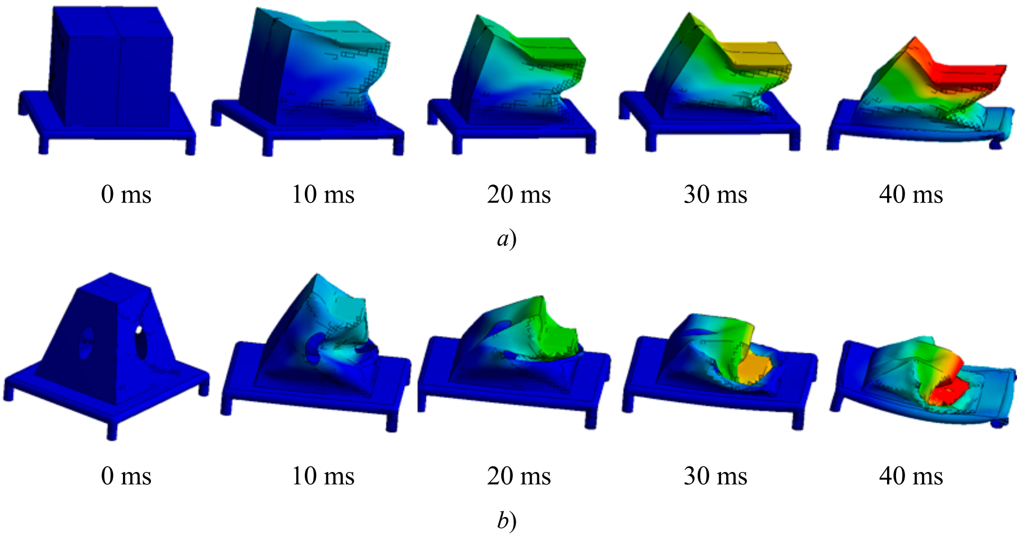


Fig. 20. Crash test of energy-absorbing elements with 40% overlap:
a) EAE of a two-section type; b) EAE of a truncated pyramid with four manufacturing holes

Testing of an energy-absorbing element with a 40% overlap is considered successful if the structure of the element was not prematurely destroyed in the collision and its stability on the front plate was preserved. As a result of testing by a crash test with a 40% overlap of the tested samples of energy-absorbing elements made of aluminum, it can be concluded that the malleability of the material allows it to withstand deformations in the structure without destruction, shifts and with the maximum possible distribution (in case of partial contact of the energy-absorbing element and the obstacle) of stresses and loads throughout the structure of the specified element.

Energy-absorbing elements from the "high efficiency" category are stable during experimental crash tests: the structural displacement relative to the horizontal axis is not significant and meets the requirements of the FSAE technical regulations. Energy absorption and overload also comply with the FSAE technical regulations.

Having analyzed the data obtained on inefficient designs of energy-absorbing elements, the proportional distribution of absorbed energy by individual structural elements of the car should be noted. When an energy-absorbing element of low efficiency (for example, made of aluminum honeycombs or a multi-component one) is hit, the required amount of energy (7350 J) is not absorbed, while the largest amount of the absorbed energy is taken by the front partition of the car or the support plate. The plate to which the energy absorbing element is attached is the second most important level of absorption of incoming energy. The rest of the energy is absorbed by the car frame. Energy-absorbing elements in case of insufficient or excessive structural rigidity absorb only 15-35% of the required energy, which is unacceptable for use as the main deformable element. The percentage of absorbed energy when struck by the structural elements of the car is given in Table 5.

Table 5

Percentage of the absorbed energy by the structural elements of the car

Name of the car structural element	High efficiency	Medium efficiency	Low efficiency
1	2	3	4
Energy-absorbing element	65–100 %	35–65 %	15–35 %
Front plate	5–15 %	15–25 %	20–35 %
Car frame	5–15 %	10–25 %	15–45 %

The presented energy-absorbing elements (with the exception of low-efficiency ones according to the gradation table for the efficiency of energy-absorbing elements) in terms of total absorbed energy meet the requirements of the FSAE technical regulations. However, it is always possible to improve the design of the energy-absorbing element due to structural changes and adjustments to the composition of the aluminum alloy.

It is known from scientific publications that energy-absorbing elements of a conical or a truncated pyramid shape are more effective than others in controlling the process of energy absorption when a car collides with a rigid obstacle (Fig. 21) [12].

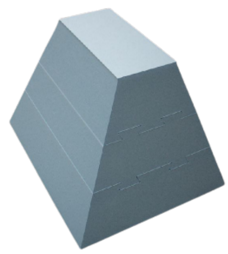


Fig. 21. Model of an energy-absorbing element with a grooved fastening system fixed with an Impax adhesive base

It was also found that the design features of energy-absorbing elements (manufacturing holes, profile bends, and so on) make it possible to control not only the deformation process, but also the geometric stability of the structure. During the analysis of the deformation of energy-absorbing elements with elliptical (or other shape) manufacturing holes, it was found that they effectively redistribute the deformation energy throughout the structure during the collision of the car with an obstacle.

In cases of insufficient rigidity of the structure of energy-absorbing elements, either its premature destruction occurs, or a slight absorption of energy with a significant displacement of the entire structure. Therefore, the developers of passive safety systems, in particular energy-absorbing elements, should take into account the possible redistribution of energy between the elements of the safety system. Thus, by changing the structural shape, size and material of manufacture of the energy-absorbing element, it is possible to redistribute energy in the collision process.

When designing passive safety elements, including energy-absorbing elements of the car, it is necessary to take into account the strong influence of the shape and size of the structure on its stability in deformation. In the process of the development of an effective energy-absorbing element, it is necessary to achieve deformation of the structure along its entire axial length.

Conclusions. The results of the study of various designs of energy-absorbing elements indicate that the distribution of stresses and deformations in them depends on the shape, size and material of EAE. When modeling and further testing energy-absorbing elements, it is necessary to achieve the deformation of the structure along its entire length.

It is established that the loss of stability of the structure of the energy-absorbing element leads to an increase in its deformation, which entails the destruction of the test sample.

Based on the simulation of the behavior of the developed variants of the designs of energy-absorbing elements during a frontal impact, it is established that:

− for rigid (non-deformable) energy-absorbing elements, the deformation is determined by the movement of the front wall of the car;

− for energy-absorbing elements of low and medium rigidity, the main part of the displacement (deformation) during impact occurs due to the deformation of the energy-absorbing element;

− the analysis of the stresses of typical structures of energy-absorbing elements that occur when hitting a rigid obstacle showed that the main zones of maximum stress concentration are located in the middle of the pipes of the frontal part of the car frame, at the attachment points of the front plate, as well as at the places of bending of the wall of the energy-absorbing element;

− the greatest drop in vehicle speed is observed at the moment of the beginning of deformation of the front plate, when the deformation of the energy-absorbing element itself is no longer sufficient. As a rule, this is a period of time from 30 to 40 milliseconds.

The analysis of the deformation of the energy-absorbing element, the front wall and the frame allowed us to establish the connectivity of all structural elements of a racing car in the field of passive safety. With excessive incoming kinetic energy, each structural element distributes and absorbs a certain percentage of energy.

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Received 21.02.2022

Revised 03.03.2022

Accepted 04.03.2022

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Claimed contributorship

L. A. Zhukov — formulation of the basic concept, goals and objectives of the study, technical development, simulations and calculations, preparation of the text, analysis of the results and formulation of the conclusions; A. L. Kuzminov — scientific supervision, technical standard control, analysis of the research results, revision of the text, correction of the conclusions.