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STUDY OF KINEMATICS OF ELASTIC-PLASTIC DEFORMATION FOR HOLLOW STEEL SHAPES USED IN ENERGY ABSORPTION DEVICES

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ABSTRACT

The paper presents the study of kinematics of elastic-plastic deformation of hollow steel shapes. This study was aimed on improvement of the force parameters in plastic deformation processes of energy absorbing construction components of hollow shapes used in transport vehicles and rise of passive safety and reliability of technical equipment. Finite element modeling (FEM) of kinematics of the processes was conducted with control of energy absorbing parameters of steel tubes with different cross sections. Specific absorbing energy of all tested tubes was calculated using QForm program for imitation of technological processes as well as for analysis of power characteristics of plastic destruction of manufactured products and essential variation of their shape. The presented results of virtual investigations of bending and upsetting in an edge of a row of hollow shapes as tubes with different cross sections displayed wide possibilities for control and management of absorption process of mechanical energy via choosing the tube design and control of simulation results of energy absorption as well as maximal force on indicating diagram of deformation process. The results of testing testified that rectangular tube of 30×70 mm cross section absorbed more energy in comparison with tubes of other cross sections. However, bending of this tube was accompanied by ultimately high force value in the beginning of deformation, what means high value of object acceleration during its impact. On the contrary, force value decreased sharply at the finishing deformation stage, what increases the risk of deterioration in protected space of an object. Additional possibilities of improvement of functional properties of hollow components presented by tubes with longitudinal dikes were revealed; their usage allows to rise safety of transport vehicles, technological machines and equipment.

Introduction

The permanent progress in machine-building and in construction leads to search of the new technical solutions regarding saving of all kinds of resources, decreasing of carbon dioxide emissions, improving of functional properties and safety of constructions. Ultra-light automotive steel bodies and suspensions (ULSAB, ULSAS) were developed actively since the beginning of 1990-ies [1-3]. At present time we can observe principally new development tendencies in transport machine-building, in particular in manufacture of private automobiles, where optimization of design and production technology will bring substantial decrease of body weight, energy consumption during manufacturing processes, operation and recycling of automobiles. Use of the new materials compositions and methods of their joining is meant here. Manufacture of automotive bodies of transport vehicles on the base of modular structures such as "shell ring — volumetric — frame constructions" **(Fig. 1)** is considered as a perspective concept during recent times. It can be noted that serious work in this direction was already done in development of passenger aircrafts and sport cars. New design and new materials technologies and new joining methods provided qualitative decrease of body weight of a transport vehicle (or of glider in aviation). A lot of composite based on carbon fibers with impregnation as well as aluminium and magnesium were used in these projects; as a result, the passenger car bode weight was decreased approximately to 200 kg.

Fig. 1. Modular structure of the "shell ring — volumetric — frame construction" type

Cumulative effect of such innovations appeared in lowering of energy consumption for acceleration and braking, of traffic load on automobile roads, railroads and so on. Recycling of secondary composites made of carbon fibers was actively used as well (they remained after pyrolysis burning of binder and can be used again). Hollow steel shapes are applied as driving components of the lower part of automobile body, e.g. in “thresholds” (see **Fig. 1**) according to DLR projects (Germany) [4]. These shapes also played the important role to protect passengers as well as accumulators and drive components in the bottoms of electromobiles from side impacts. Presence of additional “lungs” of mechanical energy absorbers in the critical zones in the front parts of automobile bodies near side members, deforming to the edge during front impact, is also very important. Protective shapes were also used in constructions of holders of automobile body and doors. Examination of structural state of hollow shapes in frame constructions during crash tests makes it possible to predict consequence of impact effect for human, for overload-sensitive devices and for valuable drive components. Many updated researches are devoted to investigation of new materials and technologies in this field [5–14].

Simulation and analysis of parameters of essential deformations of hollow shapes allows to optimize corresponding constructions. Such shapes can be used not only in transport vehicles, but also in technological equipment and building machines. However, design of such products was also determined by technological features of their manufacturing process [15–22].

Materials and methods of investigation

The aim of this research was optimization of force parameters of plastic deformation processes of energy absorbing construction components in transport vehicles and improvement of safety and reliability of technical devices.

Kinematics of elastic-plastic deformation of hollow steel shapes and tubes was conducted by two methods: three-point bending and impact along the component axis (i.e. upsetting). Both methods were accompanied by control of energy absorbing processes during loading. Kinematics of these processes was researched via finite elements modeling (FEM) for different cross sections of tubes (round, elliptic, rectangular and supplied with special internal boosters in the form of dikes) [23, 24]. Functional properties of tested shapes as energy absorbing devices for protection of passengers and equipment were evaluated in accordance with two basic criteria:

1. Value of absorbed energy.
2. Peak force value (creating acceleration or overload in protected object) during loading.

The samples were tested according to three-point bending and axial compression in the virtual finite element medium QForm [25] with geometrical modeling of the bodies to solve the elastic-plastic task. This program also allows to conduct the following operations:

- calculation of tough-plastic and elastic-plastic billet deformation;
- calculation of joint thermal and mechanical task in the system “billet — tool”;

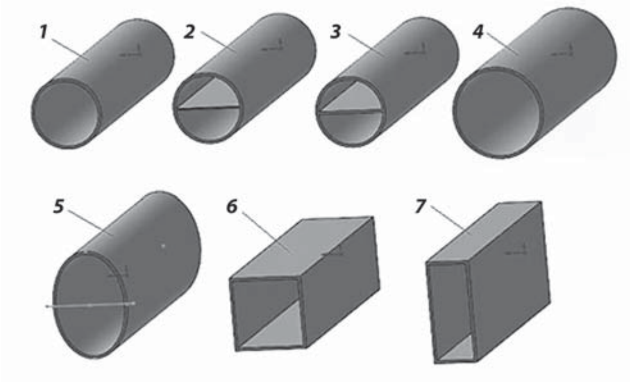


Fig. 2. The tested samples:
1 — round tube with 48 mm diameter; *2* — round tube with 48 mm diameter and longitudinal dike with 1 mm thickness; *3* — round tube with 48 mm diameter with 2 mm thickness; *4* — round tube with 64 mm diameter; *5* — elliptic tube; *6* — square tube; *7* — rectangular tube

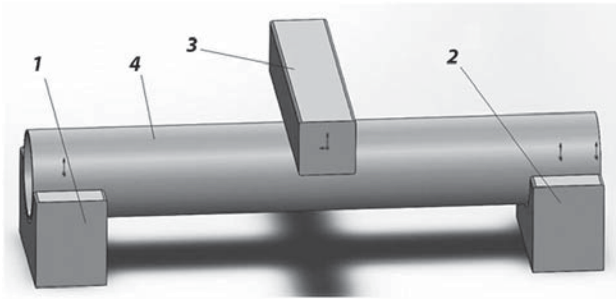


Fig. 3. Location of the tested sample before testing:
1, 2 — bottom stationary bases; *3* — movable top tool; *4* — testing sample

- calculation of deformation of several billets of different materials simultaneously.

CAD program for modeling entitled Solidworks was used for assembling of components in initial position. Kinematics and energy parameters of deformation processes for batches of hollow tubes with different shapes and dimensions were researched (**Fig. 2**).

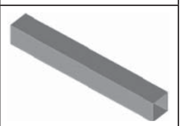
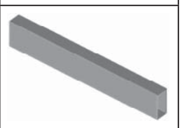
To provide bending testing[1], tube models were located on two bases 1 and 2, while active load was applied in the middle of tested samples (**Fig. 3**).

Length of samples tested for bending was 400 mm. Cross section of all tubes used in the experiments was 384 mm^2 except tubes with diameter 48 mm (with dike having width 1 mm or without this dike). All dimensions and forms of tested samples of hollow shapes are shown in the **Table 1**.

Load was applied to a movable top tool having width 50 mm. QForm VX program version was used for finite element examination of elastic-plastic deformation of tubes and elastic deformation of tool [25]. It is shown that significant bending deformation is accompanied by V-type

[1]Nguen The Vin participated in this research.

Table 1. **Dimensions and shapes of hollow tubes tested for bending**

Type of tube	Square of cross section, mm^2	Tube dimensions, mm			Dike thickness, mm	Shape
		Diameter or cross section	Length	Width		
1. Round tube, *D*	295	48	400	2	–	
2. Round tube, *D*	340	48	400	2	1	
3. Round tube, *D*	384	48	400	2	2	
4. Round tube, *D*	384	64	400	2	–	
5.Elliptic tube, $a \times b$	384	37x26	400	2	–	
6. Square tube, $a \times b$	384	50	400	2	–	
7. Rectangular tube, $a \times b$	384	30x70	400	2	–	

bending of a thin-walled tube (**Fig. 4**), and modeling of behaviour of different tubes allowed to compare features of distortion of their cross section shape.

Variation of the force value determined the acceleration value during object impact; the value of absorbing energy depending on motion and the temperature field of deforming sample were also monitored at the preset process stage. The diagrams of force value variation testified on sharp rise of the force in the beginning of the process with its consequent lowering at high deformation rates. This dynamics is connected with essential distortion of cross sections of hollow shapes in the bending area, and variation of simulating force was characterized usually by cyclic character at the certain stage.

Testing of samples for axial compression was conducted in the same way. Initial position of the components to be assembled for experiments with hollow samples having different cross sections was conducted using Solidworks program, as during testing for bending. Tested tubes with length 200 mm and different cross sections were placed between two tools and compressed along their axes. One of the tools was unmovable. The results of examined samples deformation and monitored values of absorbing energy and force are presented on the **Fig. 5**.

It is displayed that the diagram of variation of force required for motion of all tested tubes has also cyclic character (as in bending tests), what can be connected partly with consequent folding of layers of the tube sample during its axial compression.

Results of investigation

Specific absorbing energy of all tested tubes is calculated via QForm program. All values of the peak forces appeared in the early beginning of the process of tubes destruction as well as all values of absorbing energy during 100 mm motion are displayed in the **Table 2**.

Different cross sections of tubes can have some effect on energy absorbing ability and folds forming. The results of testing of different tubes can be expressed in one diagram (**Fig. 6**).

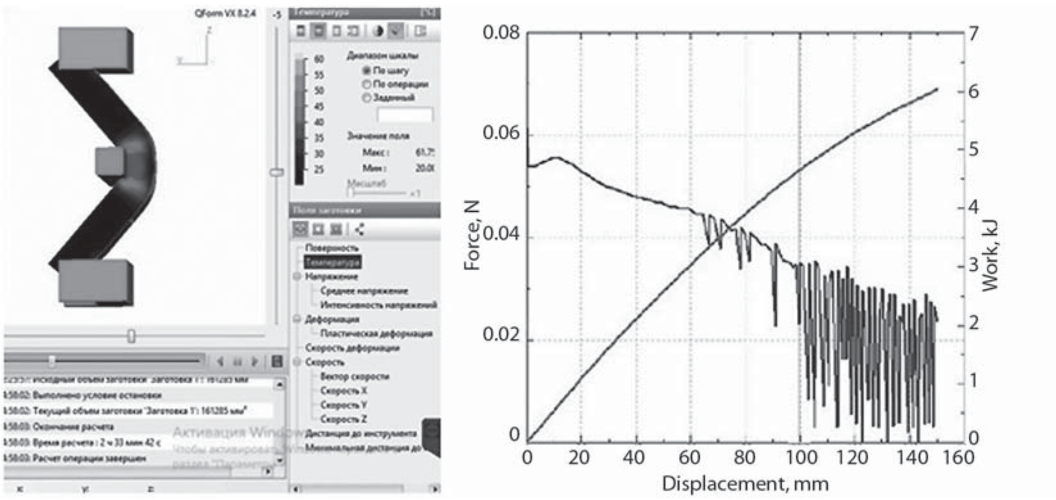


Fig. 4. Location of tested samples on the fixed stage of active top tool motion and diagrams of variation of the values of absorbing energy and deformation force

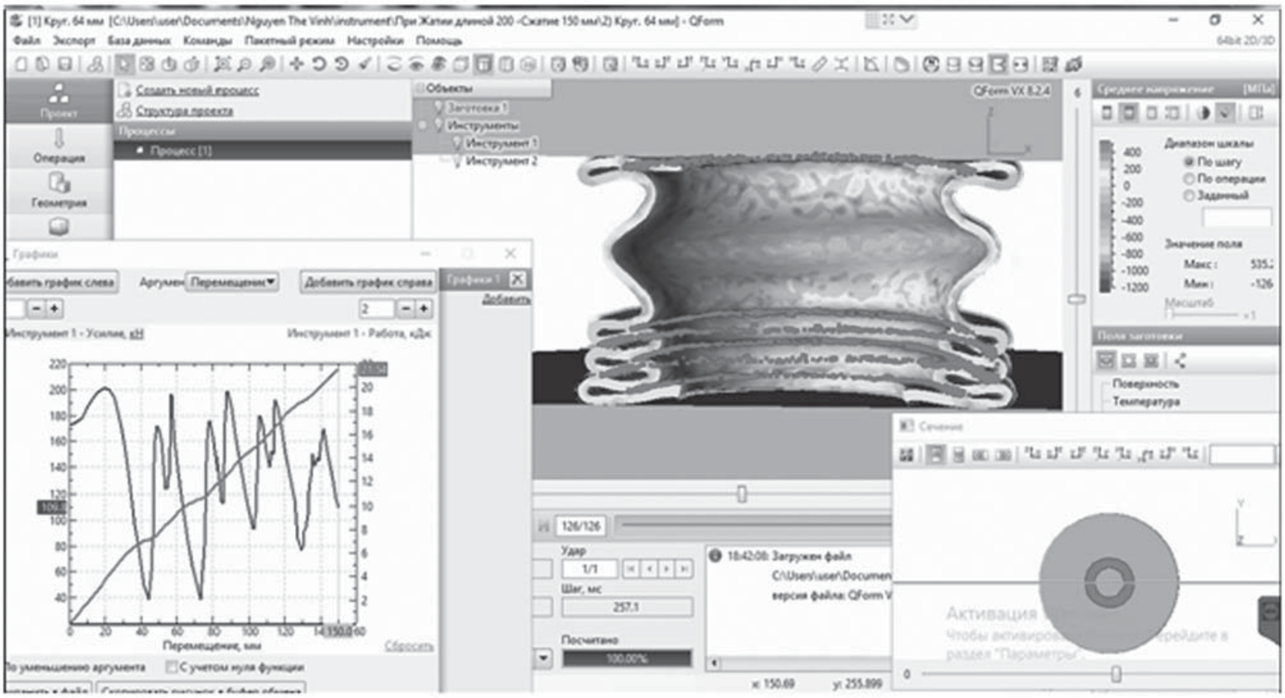


Fig. 5. Simulation of axial compression process for a round tube with 64 mm diameter

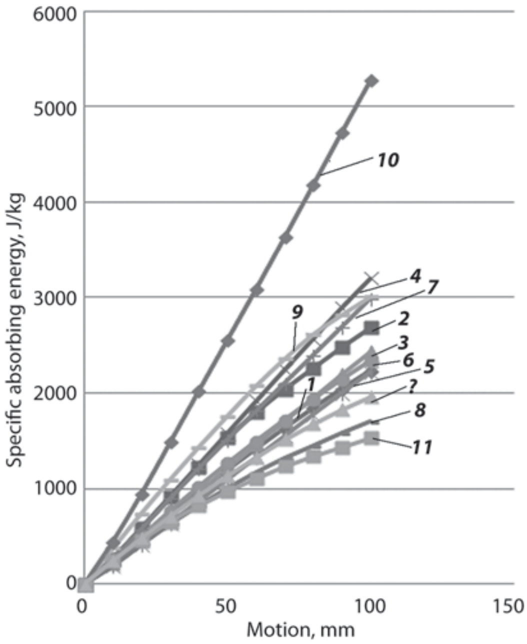


Fig. 6. Summary diagram for absorbing energy depending on motion during tubes bending or imitation of side impact in frame components:
1 — round tube with diameter 48 mm; *2* — round tube with diameter 48 mm with 1 mm dike (vertically); *3* — round tube with diameter 48 mm with 1 mm dike (horizontally); *4* — round tube with diameter 48 mm with 2 mm dike (vertically); *5* — round tube with diameter 48 mm with 2 mm dike (horizontally); *6* — round tube with diameter 64 mm; *7* — elliptic tube (vertically); *8* — elliptic tube (horizontally); *9* — square tube 50×50 mm; *10* — rectangular tube 30×70 mm; *11* — rectangular tube 70×30 mm

Table 2. **The results of experiments with tubes having different cross section shapes**

Type of tube	Peak force, kN	Absorbing energy, KJ	Specific absorbing energy, J/kg
1. Round tube with diameter 48 mm	23.81	2.022	2231
2. Round tube with diameter 48 mm with 1 mm dike (vertically)	34.09	2.806	2686
3. Round tube with diameter 48 mm with 1 mm dike (horizontally)	26.54	2.542	2433
4. Round tube with diameter 48 mm with 2 mm dike (vertically)	39.63	3.786	3202
5. Round tube with diameter 48 mm with 2 mm dike (horizontally)	27.72	2.622	2217
6. Round tube with diameter 64 mm	32.91	2.762	2336
7. Elliptic tube (vertically)	38.00	3.532	2987
8. Elliptic tube (horizontally)	26.66	2.012	1701
9. Square tube 50x50 mm	46.35	3.559	3009
10. Rectangular tube 30x70 mm	65.41	6.236	5273
11. Rectangular tube 70x30 mm	33.30	1.814	1534

The summary diagram displays that rectangular tube with cross section 30×70 mm absorbs more energy in comparison with tubes having other cross sections. However, bending of this tube accompanied by ultimately high force value in the beginning of deformation, and, respectively, by high acceleration value of the object during impact. As for the late stage of deformation the force value, on the contrary, decreases sharply, what increases deterioration risk in the protected space of an object. Testing of tubes with longitudinal dike in diameter section resulted in substantially lower value of peak load and noticeably more permanent energy absorption during the process. It should be mentioned that such tubes are not included in the list of products suggested by producers for sale.

The obtained data testify that the lines of variation of absorbing energy for rectangular tube with cross section 70×30 mm and round tube with diameter 48 mm and longitudinal dike 1mm almost coincide. However, energy absorption for the above-mentioned round tube is characterized by significantly lower peak values of force and acceleration.

Conclusions

1. Possibility of usage of QForm2d program for finite element modeling was shown as a result of the investigation. This program is devoted to imitation of manufacturing processes of products, for analysis of deformation of energy absorbing components presented by hollow shapes, used as absorbers in machine-building.

2. Presented results of virtual examinations of bending and upsetting to the edge for different hollow shapes (tubes with different cross sections) displayed wide options for control of absorbing process for mechanical energy via selection of tube design, control of results of absorbing energy simulation and maximal force value on the indicating diagram of deformation process.

3. Usage of tubes and shapes with longitudinal dikes (strengthening ribs) retards folding of thin-walled shape components owing to either rise of energy value, or lowering of overload peak value.

4. Usage of tubes and shapes with longitudinal dikes improves safety of transport vehicles, technological machines and equipment.

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