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Energy Absorption Optimization of Multiaction Plastic Working Element of Vehicle Systems under Emergency Impact Loading Conditions

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Оптимизация пластичного рабочего элемента многоразового действия в условиях аварийного ударного нагружения транспортных средств

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Проведена оптимизация геометрической формы дополнительного пластичного рабочего элемента для различных случаев ударного нагружения. Для оценки усилий сцепления тяжелых грузовых составов с разными видами амортизатора использовали конечноэлементную модель пластичного элемента. Эксперименты, включающие математическое моделирование, показали, что пластичные рабочие элементы с выпуклой образующей являются наиболее эффективными при столкновениях.

Ключевые слова: моделирование расширения трубы, пластичный элемент, оптимизация амортизатора, аварийное нагружение.

The problem of effective damping of multiple impact loads in the heavy freight trains still remains to be solved. Extreme dynamic longitudinal forces are capable of causing significant damages of the rolling-stock, track and cargo. Results of research on longitudinal dynamics of a train are important for designing the rolling-stock and braking equipment, and also for selecting the safest driving mode and forming the freight trains. Several additional plastic shock absorber designs, capable to prevent destruction of railway car, have been proposed [1, 2]. However, such devices have a single-use functionality which is inappropriate in the case of repeated collisions. The design of the additional multiaction plastic shock absorber capable of functioning several times in a short interval of time is proposed in [3]. The proposed structure [3] of a coupling between the railway cars includes additional multiaction plastic shock absorbers with “mandrel – deformable tube” working elements.

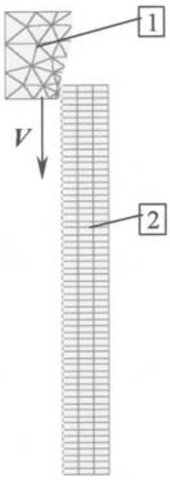
1. **The Research Problem**. At present the finite element method (FEM) is a common engineering method for calculation of structural strength of vehicle systems [4]. The plastic deformation behavior of working element has been analyzed by simulation of a thick-walled tube under shock loading conditions that characterize collisions of heavy freight trains. The stressed state is assumed to be two-dimensional with the maximal stress σ_φ, where σ_ρ is axial compressive

stress, and σ_{φ} is circumferential tensile stress. The following plasticity condition (Eq. 1) is applied

$$\sigma_{\varphi} = \sigma_{S0} + D \ln(R/R_0), \tag{1}$$

where σ_{S0} is the extrapolated yield stress, D is the modulus of hardening, and $\ln(R/R_0)$ is general tangential tensile strain.

All tests were performed by the finite element method (FEM) using the ANSYS software package [5]. FEM mesh contains plastic, dry friction, viscoplastic and solid elements. The criterion of optimization is the increase of energy absorption. Parameters of optimization are the following geometrical parameters of the working element: cone angle α, values of the tube expansion $(Rd_K - Rd_0)$, heights of cylindrical surfaces of mandrel (h_K – working and h_0 – directional), tube thickness S and radius of curvature of cone RAD. Constraints of optimization are the value of the yield stress Gt of a tube material in the center of plastic deformation, and the allowable value of the tensile strength, under condition that the plastic element works without formation of cracks in the wall of the deformable tube. Insofar as the problem is axisymmetric, calculation was carried out only for one half of the element section relative to the axis of symmetry, thus minimizing the time of calculations and making the task simpler. The FEM model is represented in Fig. 1. The properties of deformable tube *2* are described by a finite element with viscoelastic hardening properties. For the description of this element the isotropic and bilinear isotropic hardening materials are satisfactory. The mandrel properties are described by a solid-state finite element. The contact between the surfaces of the mandrel and deformable tube is simulated by 3-nodal element with Coulomb friction, as shown in Figs. 2 and 3.



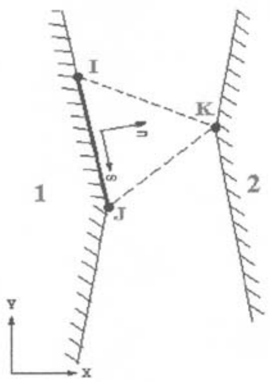


Fig. 2

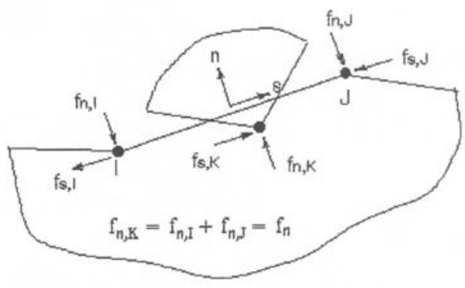


Fig. 3

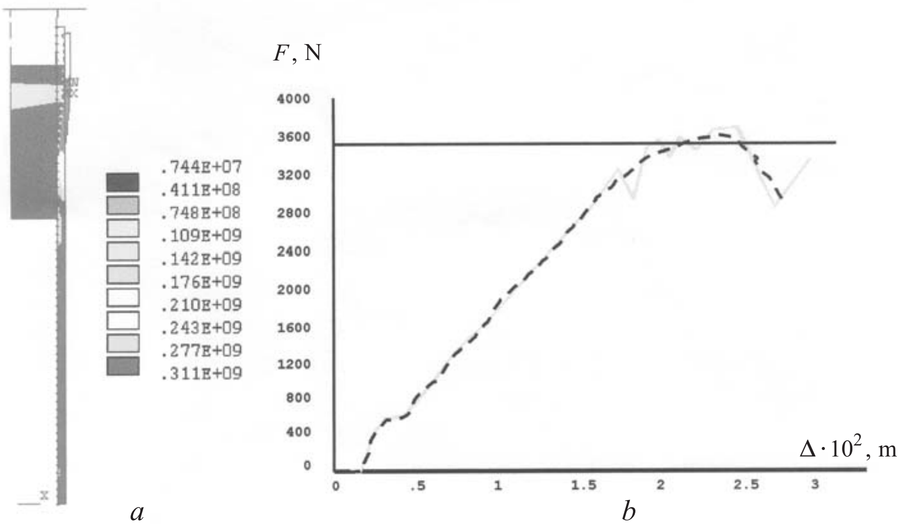
Fig. 1

Fig. 1. Initial position of the FEM model.
Fig. 2. Scheme of the contact element.
Fig. 3. Scheme of the contact forces with Coulomb friction.

The aim of numeric simulation was optimization of mandrel generating line form and dimensions by way of varying the form of friction surfaces. Simulation of the tube expansion process by indentation of mandrel with weight M (weight of the railway car) into a tube of a smaller diameter was carried out for various initial speeds of loading (Fig. 1). The complete transitional dynamic analysis for plastic elements was used in the ANSYS processor.

As a result of the analysis of the properties of a plastic working element installed on the emergency absorbing device, it is necessary to obtain: the distributions of the stresses in a wall of deformable tube for various loading speeds; modes of metal yielding with no cracks in the tube wall. For this purpose, the accelerations and efforts values that were transmitted to the freight car during the operation of a plastic element at collisions were determined.

2. **Model Validation**. For validation of the accuracy of the created finite element model in ANSYS [5] (ANSYS software package, version 5.6) a comparison with the results of a working test at static loading was carried out. The calculations were made for a reduced model. The experiment was carried out with a deformable tube (sizes $20 \times 1.3 \times 115$ mm), manufactured of steel (Steel 5), slowly loaded by a mandrel (material Steel 6) of a large diameter (values of tube expansion $Rd_K - Rd_0 = 1.2$ mm). The mandrel obliquity angle was presumed to be $\alpha = 20°$ with the cone-generating line in the form of a straight line $RAD = \infty$, tube thickness $S = 1.3$ mm (Fig. 4).



a *b*

Fig. 4. The equivalent stress (a) and expansion effort vs working stroke of mandrel (b).

The results of n tests of the experiment, performed using the initial data described above, are shown in Fig. 4. In the process of pipe expansion, the effort $P = 3560$ N with a deviation ± 182 N ($\sim 5\%$) is obtained. A comparison of the results of calculation by FEM program ANSYS and the experiment results has confirmed the accuracy of the model (Table 1). The effects of a smooth decrease in the effort during the initial phase of deformation (bending of a free end of tube Fig. 4b), with the following increase in the effort and subsequent formation of a steady center of deformation characteristic for the process of tube expansion (Fig. 5) are reflected perfectly in the model.

The numeric simulation of a plastic working element by the ANSYS software package shows a deviation of 1.4% in relation to the result of the experiment, which satisfies the research problem requirements.

T a b l e 1

Experimental and Numeric Simulation Results

Compared parameter	Experimental result (Steel 5)	ANSYS (dashed line in Fig. 4)	Relative deviation, %
Expansion effort F	$3560^{\pm 182}$ N	3610 N	+ 1.4

T a b l e 2

Characteristics of Full-Scale Plastic Element

Properties of material [Steel 30KhGS (mandrel), Steel 20Kh (tube)]			
Mechanical		Geometric	
$M = 84 \cdot 10^3$ kg	weight of the railway car	$Rd_0 = 0.026$ m	$Rd_K = 0.031$ m
$\mu = 0.15$	friction coefficient	$h_0 = 0.010$ m	$h_K = 0.005$ m
$Gt = 600$ MPa	yield stress	$S = 0.022$ m	thickness of tube
$ETAN = 0.01$ GPa	tangent modulus	$\alpha = 30°$	cone angle of mandrel
$EXXd = 198$ GPa	elastic modulus of mandrel	$\dot{x} = 1-5$ m/s	initial velocity
$EXXp = 200$ GPa	elastic modulus of tube	$\Delta_m = 0.2$ m	maximum working stroke of plastic element
$Pr = 0.3$	Poisson's ratio		
$DENS = 7850$ kg/m^3	material density		

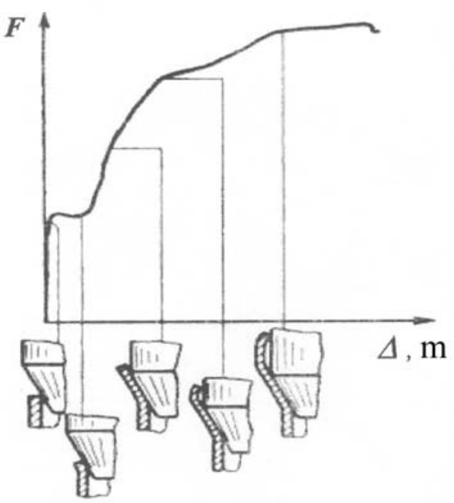


Fig. 5. Scheme of variations of the expansion effort F from working stroke Δ of mandrel.

3. **Dynamic Calculation of a Full-Scale Construction**. The dynamic calculation of plastic working element full-scale construction and optimization of the mandrel dimensions allowed us to obtain the optimal characteristics of the plastic element. The parameters of deformable tube for a plastic element (preferable length and materials) are determined in Table 2.

In the above calculations, a 4-axle open wagon with a mass of $84 \cdot 10^3$ kg was accepted as the basic type of railway car.

The dynamic behavior of a plastic working element (mandrel *1* – deformable tube *2*) for various loading speeds was investigated (see Fig. 6). As a result of the numeric simulation, the influence of the loading speed on the working element characteristics was determined, and the effects of yield stress increase and temporary resistance were revealed.

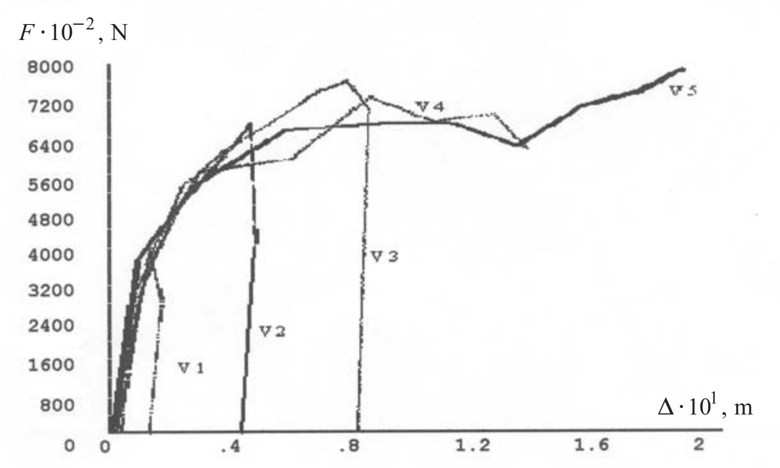


Fig. 6. Expansion effort vs working stroke of mandrel ($V_1 = 1$ m/s, $V_2 = 2$ m/s, …, $V_5 = 5$ m/s).

For obtaining the optimal working characteristics (maximal contact surface, maximal expansion effort, and minimal equivalent stress) of the plastic element, we have also performed the optimization by variation of the value of *RAD* – form of friction surface of a mandrel: convex, straight or concave generating line of a cone. The respective results are represented in Fig. 7a–c.

a *b* *c*

Fig. 7. The equivalent stress σ_e of plastic working element for different forms of the cone generating line of mandrel: (*a*) straight line, (*b*) concave line, (*c*) convex line. Speed of loading – $\dot{x} = 3.05$ m/s. [(*a*) $\sigma_e = 0.665 \cdot 10^9$ N (tube), $\sigma_e = 1.160 \cdot 10^9$ N (mandrel); (*b*) $\sigma_e = 0.647 \cdot 10^9$ N (tube), $\sigma_e = 1.400 \cdot 10^9$ N (mandrel); (*c*) $\sigma_e = 0.626 \cdot 10^9$ N (tube), $\sigma_e = 1.010 \cdot 10^9$ N (mandrel).]

During the optimization it was discovered that for $RAD = \infty$ expansion effort insignificantly exceeds the effort for convex surface only in the end of working stroke of mandrel (Fig. 8). The use of a concave surface of mandrel (Figs. 7b and 8) gives the maximal expansion effort $F = 90 \cdot 10^4$ N, but the stress in mandrel reaches the limiting values for the chosen material (steel 30KhGS).

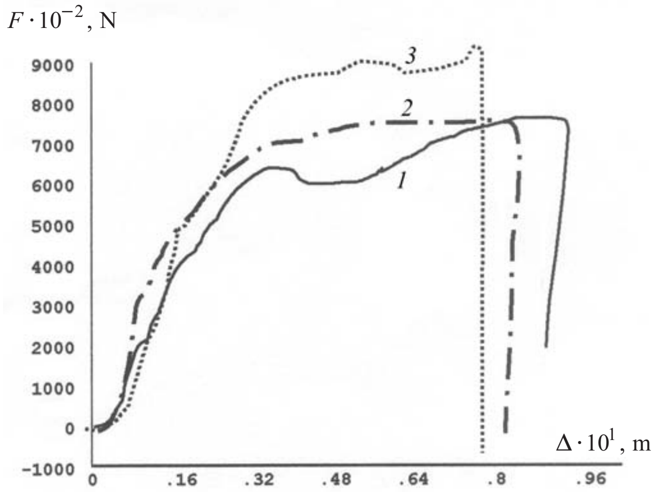


Fig. 8. Calculation of expansion effort vs working stroke of mandrel for different forms of cone generating line: (*1*) $RAD = \infty$; (*2*) $RAD = 0.04$ m; (*3*) $RAD = 0.04$ m, $\dot{x} = 3.05$ m/s.

Thus, concave friction surface of mandrel requires a more durable (expensive) brand of steel to be used.

Therefore, mandrel form with a convex friction surface $RAD = 0.04$ m (Figs. 7c and 8) is accepted as closest to the optimum from the point of view of maximal energy absorption of a plastic element. The expansion effort $F = 74 \cdot 10^4$ N at working stroke $\Delta = 0.0831$ m is insignificantly less than at $RAD = \infty$ ($F = 74 \cdot 10^4$ N, $\Delta = 0.0939$ m), but the contact surface length is maximal (Fig. 7c), while the equivalent stress is minimal and does not reach its allowable value.

Conclusions. As a result of the optimization, the energy absorption of a plastic element has been brought to the maximum by improvement of mandrel geometry, namely: the forms of cone friction surface, cone angle, values of tube expansion, and heights of cylindrical surfaces of mandrel. The effects of interaction of dry friction, elastic and solid elements are revealed. Comparison of numerical results and experimental results shows the satisfactory accuracy of calculation. Mandrel form with a convex friction surface ($RAD = 0.04$ m) is calculated as closest to the optimum from the point of view of maximal energy absorption of a plastic element for this case.

Numerical simulation and optimization of a plastic working element significantly increases the accuracy of a new comprehensive coupling model by way of including the emergency multiaction plastic shock absorbers. The model of plastic element can be used for the construction of a complex model of longitudinal dynamics of heavy trains.

Резюме

Проведено оптимізацію геометричної форми додаткового пластичного робочого елемента для різних випадків ударного навантаження. Для оцінки зусиль зчеплення важких вантажних потягів із різними видами аморти-

заторів використовували скінченноелементу модель пластичного елемента. Експерименти, до складу яких входило математичне моделювання, показали, що пластичні робочі елементи з опуклою твірною є найбільш ефективними при зіткненнях.

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