The passive safety system of a high-speed multiple-unit train

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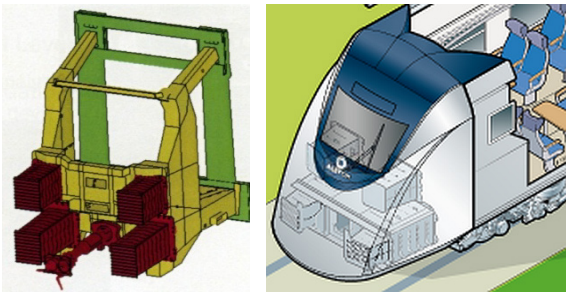
Abstract. The designing of modern high-speed multiple-unit trains in Ukraine should be carried out accounting for passive safety systems (PSSs) which include energy absorption devices (EADs). In the cases of trains collisions with obstacles these systems must automatically work to increase the passenger transportation safety, to reduce the risk of injury and death of passengers and service personnel, to minimize rolling stock damage. On the base of European experience in power head passive protection, a three-dimensional geometric model of the domestic power head frontal part with energy absorption devices containing cellular elements was developed. The protective devices for the power head and energy absorption devices installed in inter-car connections were proposed using the experience of development of the EP20 locomotive energy absorption device and results of its prototype crash test. The scientific methodology was developed to evaluation the EAD parameters. Finite-element models for studying the plastic deformation of EAD designs at impact and discrete-mass mathematical models for studying the dynamic loading of reference multiple-unit train vehicles in emergency collisions were developed in accordance with the DSTU EN 15227 requirements. As a research result, the parameters of the EAD designs have been obtained and compliance of the developed passive safety system with regulatory requirements has been proven.

1 Introduction

The designing of modern high-speed multiple-unit trains in Ukraine should be carried out accounting for passive safety systems (PSSs) which include energy absorption devices (EADs). In the cases of trains collisions with obstacles these systems must automatically work to increase the passenger transportation safety, to reduce the risk of injury and death of passengers and service personnel, to minimize rolling stock damage.

In the EU countries, the passive protection of the multiple-unit train in emergency collisions is regulated by EN 15227 [1]. In Ukraine standard DSTU EN 15227 [2] which is identical to the European standard EN 15227 has been adopted. The passive protection of European passenger rolling stock is organized in accordance with the requirements of EN 15227 in such a way that the main part of the collision energy of a multiple-unit train with an obstacle is absorbed by the power head EADs. The power head is equipped with a two-level system of EADs (Fig. 1) located at the level of the coupling device (lower level EADs) and in the front window sill above the level of the coupling device (upper level EADs) [3-5].

As a rule, box or tubular structures with various initiators of deformations and filling options are used as EADs. In an emergency collision, energy is absorbed as a result of plastic deformation, flaring or cutting of the EAD elements. The cabin frame with the control panel is a reinforced safety zone for the survival and driver's evacuation at a collision. The power head has a supporting body, which ensures the possibility of EADs operation at a collision. The intermediate coaches of the multiple-unit train are equipped with anti-lift and coupling devices with energy-absorbing elements.



422 train (Bombardier) Coradia train (Alstom)

Fig. 1. EADs of power head frontal part (European trains)

There are no real projects on creation of the domestic power head with PSS in Ukraine now. The first Ukrainian electric train EKr1 ("Tarpan") with PSS [6] was developed in 2013. PSS of its power head was developed by the Polish company IC engineering in accordance with orientation to the EN 15227 requirements. This PSS included nine box steel energy absorption devices. There were two EADs at the coupling level, two EADs at the driver's cab floor level and five EADs in the window-sill part [7]. The stainless steel support of the power head design was equipped with the SA-3 automatic coupler, which could move back into the under-coach space at a collision. Other end

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of the power head was equipped with clearance-free couplers with absorbing devices R-2P. Power head PSS effectivity has not been confirmed with crash tests.

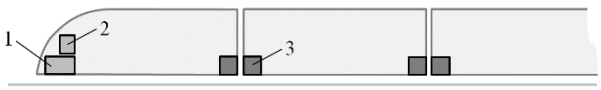
The development of domestic multiple-unit train with PSS is an important problem caused by the growth of railway passenger traffic speeds and orientation towards European integration, the need to update rolling stock with adherence to DSTU EN 15227.

2 Formulation of the problem

This article is dedicated to the development of the passive safety system for a domestic high-speed multiple-unit train.

According to DSTU EN 15227 a reference high-speed multiple-unit train consists of a power head with a mass of 80 tons and four coaches with a mass of 64 tons behind it. These masses are typical for a power head and intermediate coach, which are exploited on domestic railways with a width of 1520 mm.

The proposals on passive protection of a domestic power head are developed accounting for European power head passive protection experience [7]. It is assumed that the longitudinal force at which the shift of couplers back into the under coach space occurs is 2.0 MN. The longitudinal force at which plastic deformations occur in the power head structure elements is 4.2 MN, in coach structure elements is 3.0 MN. The protective devices for the frontal part power head and for inter-car connections were proposed using the experience of development of the EP20 locomotive energy absorption device [8, 9] and results of its prototype crash test [10]. The scheme of EADs arrangement in a train is shown on Fig 2.



1 – lower level energy absorption devices (EADs 1);
2 – upper level energy absorption devices (EADs 2);
3 – lower level energy absorption devices (EADs 3)

Fig. 2. The scheme of EADs arrangement in a train

Designs of energy absorption devices are shown on Fig 3.

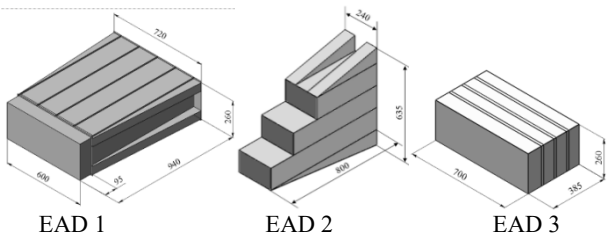


Fig. 3. Designs of energy absorption devices

It has been recommended to install two EAD 1 at the coupling level in a power head frontal part, two EAD 2 in its window-sill part and two EAD 3 in the inter-car connection at the coupling level. EAD 1 design includes two elements located sequentially. Element 1 is a box with a single-layer package of hexagonal honeycombs inside. Element 2 is a truncated pyramid of honeycombs with triangular cells. EAD 2 design has three steps in element 2 form. EAD 3 design has been developed on the basis of element 1.

A three-dimensional geometric model of the power head frontal part with lower and upper level energy absorption devices was developed. It is shown on Fig 4.

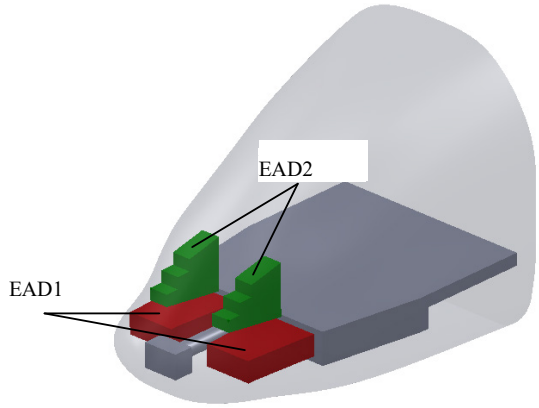


Fig. 4. Model of the power head frontal part with EADs

It is necessary to demonstrate ensuring the reference train passive safety in collision scenarios according to DSTU EN 15227 criteria. Scenario 1 is a frontal collision of two identical reference trains at a speed of 36 km/h. Scenario 2 is a frontal collision of a reference train at a speed of 36 km/h with an 80 t freight wagon. Scenario 3 is a frontal collision of a reference train at a speed of 110 km/h with a 15 t large road vehicle as a deformable obstacle on a level crossing. The mandatory DSTU EN 15227 requirement is to save intact space for survival of passengers and the train crew (the safety zone or the survival space) throughout the deformation of energy absorption devices which are included in the PSS. Local plastic deformation and local buckling are acceptable if it is demonstrated that they are sufficiently limited, so as not to reduce the survival spaces. When subject to the defined scenarios, the reduction in length of passenger survival space shell be limited to not more than 50 mm over any 5 m length. The value longitudinal deceleration in the survival spaces shall be limited to 5 *g* (*g* is the acceleration of gravity) for Scenario 1 and Scenario 2 and 7,5 *g* for Scenario 3. The method of determining the mean deceleration for each considered coach in the train should correspond to the time from when the net contact force on the coach exceeds zero to the time when it next falls again to zero.

3 Mathematical simulations

The scientific methodology was developed to evaluation the EAD parameters. This methodology includes the development of a conceptual diagram of the EAD deformation upon impact; the determination of its energy absorbing capacity as a result of mathematical modeling of the dynamics of reference a multiple-unit train with PSS at collisions; the correction of the conceptual diagram of the EAD deformation to meet the requirements of DSTU EN 15227; choice of parameters

of the EAD design with the required energy absorbing capacity using finite element modeling of the EAD plastic deformation at impact; confirmation of the compliance of the developed PSS with the criteria of DSTU EN 15227.

Finite-element models for studying the plastic deformation of EAD designs at impact and discrete-mass mathematical models for studying the dynamic loading of reference multiple-unit train vehicles in emergency collisions were developed in accordance with the DSTU EN 15227 requirements.

3.1 Finite-element models for studying the plastic deformation of EAD designs at impact

The mathematical models have been developed to analyze EAD designs plastic deformation at impact by rigid vertical wall (impactor). Finite-element simulations have been carried out with the using of the Krieg and Kay incremental model of plasticity [11] to describe the nonlinear elastic-plastic material properties under impact taking into account the kinematic hardening. This model is based on the bilinear approximation of the true stress-strain diagram. The breaking point of such a two-part piecewise linear curve corresponds to the dynamic yield stress, which depends on the strain rate. The Simonds-Cowper dependence has been used to calculate the true dynamic yield point [12].

The finite-element mathematical models for the nonlinear dynamic analysis of the EAD design plastic deformation at impact have been developed using special plate elements with four or three nodes, each of them has three linear and three angular displacements, as well as three linear velocities and accelerations relative to the node coordinate system. The impactor has been simulated by solid elements with three linear displacements, velocities and accelerations at each node.

As a result of the solution of the obtained differential equations by successive loading method [13] nodal displacements, velocities, accelerations, deformations, stresses and nodal forces at different moments of time at a given initial collision speed have been determined. The dependence of the contact force (integral over the contact area from the distributed contact stresses) between the investigated EAD design and the impactor on the longitudinal displacement of the impactor mass center at the current moments has been plotted taking into account the permissible low-pass filter [2].

3.2 Mathematical model to study the frontal collision of reference multiple-unit trains

The mathematical model and program modules were developed to study a frontal collision of two identical reference multiple-unit trains at a speed of 36 km/h (Scenario 1 of DSTU EN 15227). Calculation scheme (Scenario 1) is shown on Fig 5.

Reference trains are considered as chains of solid bodies connected with one another via essentially nonlinear elements. The force characteristic of an inter-car connection accounts for the operation of the absorbing apparatus of the coupling devices, the possibility of the automatic coupler shifting back into the under coach space at a collision, EAD plastic deformations, and the possibility of plastic deformations in the coach structures [14]. The process of a frontal collision of trains on a straight track section is described by a system of differential equations

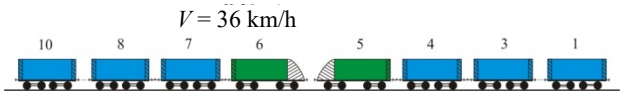


Fig. 5. Calculation scheme (Scenario 1)

$$
\begin{aligned}
&\dot{v}_i = m_i^{-1}\left[S_i - S_{i+1} + F_i\right] \ (i = 1,\ 2, \cdots, 2N);\\
&\dot{q}_i = v_{i-1} - v_i \quad (i = 2,\ 3, \cdots, 2N);\\
&q_i = x_{i-1} - x_i \ \ (i = 2,\ 3, \cdots, 2N);\\
&S_i = S_i(q_i, \dot{q}_i) \quad (i = 2,\ 3, \cdots, 2N);\\
&S_1 = S_{2N+1} = 0;\\
&v_i = v_{i0}\,(i = 1, \cdots, N);\\
&v_i = 0 \quad (i = N+1, \cdots, 2N),
\end{aligned}
\tag{1}
$$

where m_i – mass of the i-th coach; x_i, v_i, $\dot{v}_i$ – displacement, velocity and accelerations of the i-th coach; S_i – a longitudinal load between the i-th and $(i-1)$-th coaches; q_i, $\dot{q}_i$ – relative displacements and velocities of the i-th coach; F_i – external force acting on the i-th coach; N – the number of coach in each train.

The mathematical model for the study of a frontal collision of the reference multiple-unit train at a speed of 36 km/h with an 80 t freight wagon (Scenario 2 of DSTU EN 15227) has been developed. It is based on the above model of a collision of identical multiple-unit trains with account for the force characteristics of power head – freight wagon interaction in an emergency [15]. Calculation scheme (Scenario 1) is shown on Fig 6.

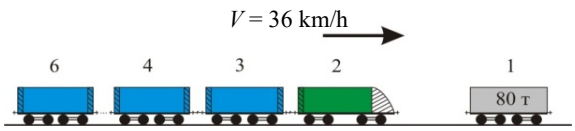


Fig. 6. Calculation scheme (Scenario 2)

Scenario 3 of DSTU EN 15227 characterizes a collision of a reference multiple-unit train at a speed of 110 km/h with a 15 t large road vehicle on a level crossing. Standard DSTU EN 15227 formulates a criterion for the mathematical simulation of this road vehicle as a large deformable obstacle (LDO). The development of LDO model envisages the construction of a geometrical model of the obstacle, its finite-element scheme and the determination of its physical and mechanical parameters. The LDO model was developed in compliance with the DSTU EN 15227 requirements [16]. Finite-element models were developed to determine the force characteristics of interaction between

the proposed EADs of power head frontal part and an LDO [17]. The mathematical model for the study of a collision of a reference train with a large road vehicle (Scenario 3) was developed on the base of a mathematical collision model for identical multiple-unit trains (Scenario 1) taking into account the determined force characteristics of interaction between the EADs of power head frontal part and an LDO and the in-collision work of the power head design [18]. Calculation scheme (Scenario 3) is shown on the Fig 7.

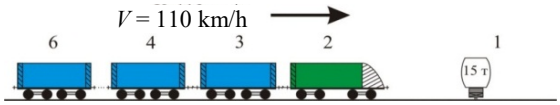


Fig. 7. Calculation scheme (Scenario 3)

The proposed mathematical models make it possible to obtain the average values of the coaches accelerations and plastic deformations for comparison with the permissible values according to DSTU EN 15227 criteria.

4 Results

The developed scientific methodology and mathematical models have been used to select the EADs parameters to carry out the collision scenarios according to DSTU EN 15227.

Energy absorbing capacity values of considered EADs have been obtained as a result of mathematical modeling of the dynamics of a reference train with PSS during collisions. As a result of finite-element modeling of plastic deformation of EAD designs at impact parameters of EAD 1, EAD 2, EAD 3 designs with energy absorbing capacity 0.95 MJ, 0.12 MJ and 0.3 MJ respectively are determined.

The research of the dynamic response of train units with the proposed PSS at a frontal collision of two identical reference multiple-unit trains at a speed of 36 km/h (Scenario 1) has been carried out. Results for Scenario 1 are shown on Fig. 8-13.

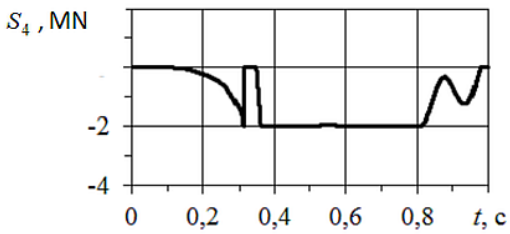


Fig. 8. The dependence of the longitudinal load between the 3-th coach and the 4-th coach on time (Scenario 1)

It has been determined that the average absolute values of the coach accelerations do not exceed 5 *g*. The average value of the absolute plastic deformations in the designs of power heads and coaches does not exceed 0.05 m (0.01 m only for the 7-th coach). It was found that the proposed passive protection meets the DSTU EN 15227 requirements for Scenario 1.

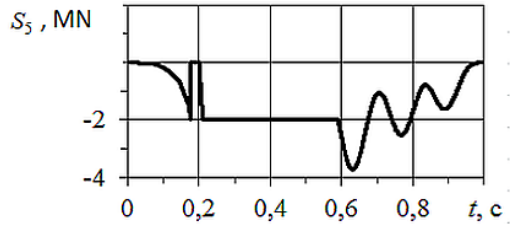


Fig. 9. The dependence of the longitudinal load between the 4-th coach and the 5-th power head on time (Scenario 1)

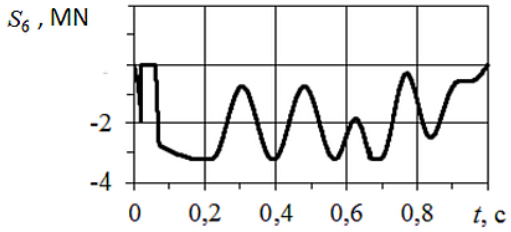


Fig. 10. The dependence of the longitudinal load between power heads on time (Scenario 1)

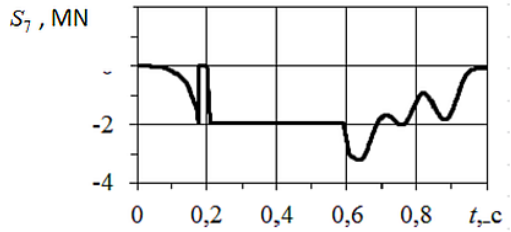


Fig. 11. The dependence of the longitudinal load between the 6-th power head and the 7-th coach on time (Scenario 1)

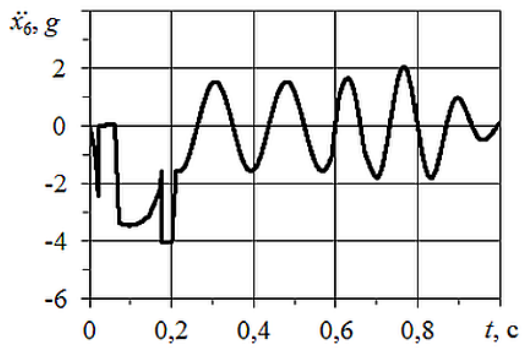


Fig. 12. The dependence of the 6-th power head acceleration $\ddot{x}_6$ on time (Scenario 1)

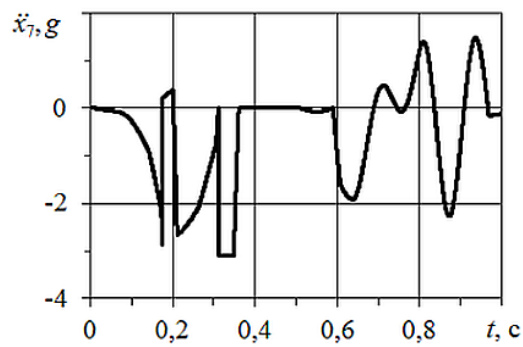


Fig. 13. The dependence of the longitudinal acceleration $\ddot{x}_7$ of the 7-th coach on time (Scenario 1)

The research of the dynamic response of train units with the proposed PSS at the frontal collision of the reference multiple-unit train at a speed of 36 km/h with an 80 t freight wagon (Scenario 2) has been carried out. Results for Scenario 2 are shown in Tab. 1.

Tab. 1. Results for Scenario 2

The coach number	Maximum absolute values		Average absolute values	
i	S_i, MN	$\ddot{x}_i$, g	S_i, MN	$\ddot{x}_i$, g
2	3,25	4,06	2,76	2,76
3	2,00	3,11	1,74	1,96
4	2,00	2,45	1,15	1,27
5	1,87	2,02	0,49	0,38
6	1,31	2,05	0,31	0,49

It has been determined that the average values of the coach accelerations do not exceed 5 g. There are not plastic deformations in the designs of power heads and coaches. It was found that the proposed passive protection meets the DSTU EN 15227 requirements for Scenario 2.

The research of the dynamic response of reference multiple-unit train units with the proposed PSS at the frontal collision of the train at a speed of 110 km/h with a 15 t large road vehicle on a level crossing has been carried out. For this Scenario 3 the dependence of the longitudinal acceleration of the power head on time is shown on the Fig 14-17.

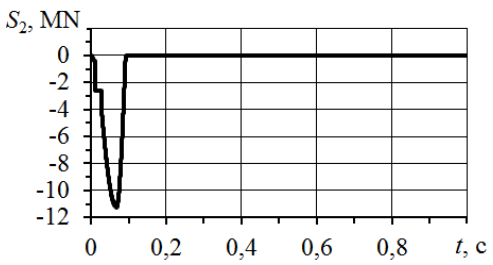


Fig. 14. The dependence of the longitudinal load between the power head and OLD on time (Scenario 3)

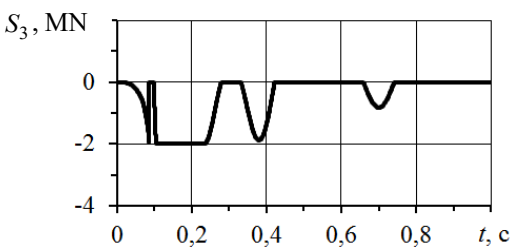


Fig. 15. The dependence of the longitudinal load between the power head and the 3-th coach on time (Scenario 3)

It was established that the maximum level of the average absolute values of the longitudinal accelerations of the train units is 7.29 g. This is acceleration level of the power head. The average absolute values of the longitudinal accelerations of the train units do not exceed 7.5 g according to DSTU EN 15227.

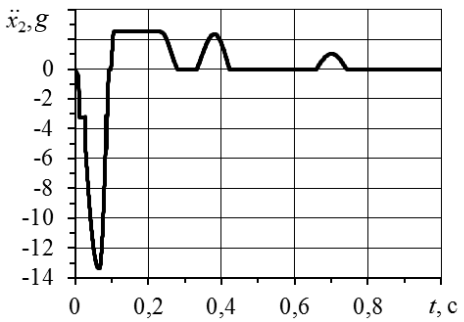


Fig. 16. The dependence of the longitudinal acceleration $\ddot{x}_2$ of the power head on time (Scenario 3)

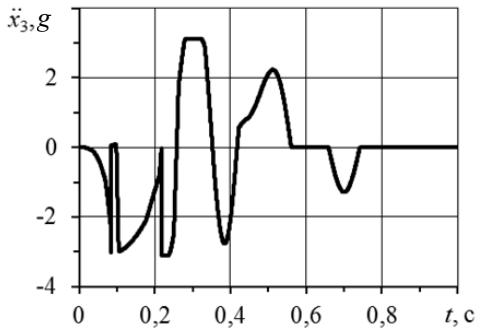


Fig. 17. The dependence of the longitudinal acceleration $\ddot{x}_3$ of the 3-th coach on time (Scenario 3)

It should be noted that the energy absorption devices in the inter-car connections between intermediate 4-th coach and 5-th coach, between 5-th coach and 6-th do not work, since the forces do not reach the level of 2 MN.

Absolute plastic deformations are observed only in the 25 m length power head design. This deformation value is 0.24 m. It does not exceed 0.05 m for every 5 m of a power head design length in accordance with the DSTU EN 15227 requirements. For the solving the issue of the presence, reduction and elimination of plastic deformations in the structural elements of the power head design it is necessary to solve a nonlinear dynamics problem to determine the stress-strain state of a power head design using its detailed spatial finite element scheme. In this case, the intermediate coaches can be represented by separate masses. The proposed passive protection of the power head and intermediate coaches of the reference multiple-unit train meets the criteria of DSTU EN 15227 for Scenario 3.

In general, the compliance of the developed passive safety system with regulatory requirements has been proven.

5 Conclusion

On the base of European experience in power head passive protection, a three-dimensional geometric model of the domestic power head frontal part with energy absorption devices containing cellular elements was developed.

The protective devices for the power head and energy absorption devices installed in inter-car connections were proposed.

The scientific methodology was developed to evaluation the EAD parameters. Finite-element models for studying the plastic deformation of EAD designs at impact and discrete-mass mathematical models for studying the dynamic loading of reference multiple-unit train vehicles in emergency collisions were developed in accordance with the DSTU EN 15227 requirements.

As a research result, the parameters of the EAD designs have been obtained and compliance of the developed passive safety system with regulatory requirements has been proven.

References

1. EN 15227. Railway applications. Crashworthiness requirements for railway vehicle bodies (2020)
2. Zaliznychnyi Transport. Vymohy do udarostiikosti reikovykh transportnykh zasobiv DSTU EN 15227: 2015 (EN 15227:2008+A1:2010, IDT) (2016)
3. J. Roberts , B. Fraikin, D. Leveque, Innovation in Passive Safety and Interior Design, **17**, 237-248 (2008)
4. A. Bruggemann, Zheleznye dorogi mira, **5**, 37-49, (2010)
5. Coradia regional trains. Meeting your specific needs, URL: https://transitio.se/wp-content/uploads/2021/10/Coradia_broschyr.pdf
6. G. S. Ignatov, Lokomotiv-inform, **10,** 28-33 (2012)
7. M. Sobolevska, D. Horobets, S. Syrota https://iopscience.iop.org/article/10.1088/1757-899X/985/1/012016/pdf
8. M. Sobolevska, I. Telychko, Transport problems, **12,** 51-62 (2017)
9. N. Yu. Naumenko, M. B. Sobolevska, O. M. Markova, H. N. Kovtun, D. V. Horobets, V. V. Maliy, S. A. Syrota, I. Yu. Khizha, Techical mechanics, **3**, 98-111 (2018)
10. M. B. Sobolevska, D. V. Horobets, S. A. Syrota, I. V. Telichko, Techical mechanics, **2**, 91-105 (2016)
11. R. D. Krieg, S. W. Key, ASME, **20,** 125-137 (1976)
12. G. R. Cowper, P. S. Symonds, *Strain Hardening and Strain Rate Effects in the Impact Loading of Cantilever Beams* (Brown University, 1957)
13. J. Oden *Konechnye Elementy v Mekhanike Sploshnykh Sred* (Moskva, 1976)
14. M. B. Sobolevska, N. Yu. Naumenko, D. V. Horobets, Techical mechanics, **2**, 66-79 (2020)
15. M. B. Sobolevska, N. Yu. Naumenko, D. V. Horobets, Techical mechanics, **3**, 79-90 (2020)
16. M. B. Sobolevska, D. V. Horobets, S. A. Syrota Techical mechanics, **2**, 90-102 (2018)
17. M. B. Sobolevska, D. V. Horobets, S. A. Syrota Techical mechanics, **4**, 118-128 (2021)
18. M. B. Sobolevska, D. V. Horobets, Techical mechanics, **1**, 51-66 (2022)