Development of passive protection devices for a power head of a high-speed multiple unit train at its collisions

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Abstract. Ukrainian passenger multiple power heads with passive safety systems damage and to minimize consequences at collisions energy absorption devices (EADs) for power head EAD 2, EAD 3 designs have been developed locomotive EADs creation and EAD prototype elements which are located sequentially, hexagonal honeycombs inside. Element triangular cells. EAD 2 design has three developed on the basis of element 1. It has been head frontal part at the coupling level, two E AD 3 in the inter-car connection at the coupling level plastic deformation at an impact has been

1. Introduction

Increasing the speed and improving safety of passenger railway transportation are actual problems in Ukraine. Their solution directly influences on the technical and economic performance indicators of railway transport and determines its competitiveness in the world transport service market. The passenger multiple-unit train upgrading supposes on creation of new power heads which are equipped with an effective active protection to prevent collisions and with passive safety systems to operate automatically at accident collisions of trains with obstacles and to create conditions for passengers and train staff safety, to reduce rolling stock damage and to minimize emergency consequences.

This article is devoted to development energy absorption devices which are included in a passive safety system of a high-speed multiple-unit train power head at collisions on the 1520 mm gauge railways.

The analysis of the normative requirements which act in EU countries, Ukraine, the Customs Union countries – Technical Regulation of the TC “On the safety of railway rolling stock” [3], GOST R 53076-2008 (structural requirements of railway vehicle bodies) [4] and GOST 32410-2013 (requirements for crash- systems) [5]. In 2016, Ukraine adopted standards DSTU EN 12663: 2015 (EN 12663-1: 2010, IDT) [6] and DSTU EN 15227: 2015 (EN 15227: 2008 + A1: 2010), IDT) [7]. Now these standards are in action in Ukraine [8] and [9].
In accordance with DSTU EN 12663, the driver’s cab design should be capable to stand compressive longitudinal loads without plastic deformation: 1.5 MN at the coupler level (or buffer level), 0.4 MN at 150 mm above the top of the structural floor at head stock, 0.3 MN at the level of the window-sill and 0.3 MN at the level of the cant rail.

DSTU EN 15227 regulates the mandatory availability of passive safety systems in the multiple-unit train vehicle designs. DSTU EN 15227 defines collision scenarios, reference trains, and conformity criteria for railway vehicles with PSS. For experimental and computational verification of PSS standard DSTU EN 15227 defines four collision scenarios, which are characterized by a set of collision conditions (mass values, initial impact speeds and other parameters of collision objects). 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. Scenario 4 is a collision of a train with a low obstacle (car, animal, rubbish) on a level crossing.

A reference train for power head design development consists of a power head and four vehicles behind it. It is necessary to demonstrate the fulfillment of tasks of ensuring the reference train passive safety in scenarios of collisions according to DSTU EN 15227 criteria. The mandatory DSTU EN 15227 requirement is to save intact space for survival of passengers and the train crew (safety zone) 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. The mean 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.

At present, an actual and important task for Ukraine is to create a domestic high-speed multiple-unit train, especially its power head with its own develop PSS according to DSTU EN 12663 and DSTU EN 15227 requirements. It should be noted that the use of DSTU EN 15227 is impossible without rectification of reference trains and obstacles characteristics and without taking into account such features as combined draw-and-buffer gear devices, overall dimensions and mass requirements for power heads and coaches operating on 1520 mm gauge railways.

2. Analysis of existing energy absorption devices for power head passive protection

Today, we can see an active development of power head passive safety systems in Europe, China, South Korea, the Russian Federation, Kazakhstan and other countries. Patent-bibliographic researches of existing energy absorption devices for power head of high-speed passenger multiple-unit train at emergency collisions have been carried out [9-15]. Power head EADs absorb the main part of the accident collision energy. The front end of European power head is equipped with a lightweight push-back automatic coupler containing energy absorbing elements, an obstacle deflector, a multi-level system of energy absorbing devices which is usually placed outside the driver’s cab and anti-climb units. The driver’s cab frame is a safety zone for the driver’s survival and evacuation at a collision. As a rule, lower-level energy absorbing devices are placed on the coupling level. EAD design is a box or a tubular type design with 1 MN energy capability. At accident collisions, impact energy is absorbed as a result of plastic deformation, flaring, or cutting of EAD design elements. An upper-level EAD design is placed in driver’s cab window-sill part above the coupling level. It is a box design with various strain initiators and filling. The rear end of a European power head is equipped with couplers and anti-climb units usually including energy-absorbing components.

An upper-level EAD is not used in Russian power head designs unlike European ones with PSS. It is connected with different requirements of EN 15227 and GOST 32410-2013 in the scenarios of a train collision with an obstacle on a level crossing. According to EN 15227, 15 t deformable obstacle with a height of 3.2 m is used. According to GOST 32410-2013 10 t low non-deformable obstacle with a height of 2.2 m is considered.

There are no real projects on creation of the domestic power head with in-house design PSS in Ukraine now. The first Ukrainian electric train (“Tarpan”) with PSS was developed in 2013 [15]. Only its power head had a PSS. It was developed by the Polish company IC engineering in accordance with
the specification and orientation to the EN 15227 requirements. The power head front end was equipped with two steel box EADs at the coupling level, two steel box EADs at the driver’s cab floor level and five steel box EADs in the window-sill part. The train power head had a stainless steel support design equipped with the SA-3 automatic coupler, which could move back into the under coach space at a collision. Other end of the power head was equipped with clearance-free couplers [20] with absorbing devices R-2P. Power head PSS effectivity has not been confirmed with crash tests.

3. Proposals on passive protection of a domestic power head

The proposals on passive protection of a domestic power head are developed. It is advisable:

- to integrate in the power head design lightweight push-back automatic coupler containing energy absorbing elements which do not create obstacles for the passive safety system work at collisions, an obstacle deflector, EADs with anti-climb units in a power head front end and in its rear end;
- to develop designs of power head body and underframe which have to be stronger in the longitudinal direction. These designs should have power elements to limit the safety zone for the survival and evacuation of passengers. These designs should allow to operate EADs adequately without loss of their total bearing capacity in the collision scenarios;
- to take such allowed values of longitudinal dynamic loads at collisions according to DSTU EN 15227 scenarios as 4,2 MN for a power head underframe, 3,0 MN for a coach power head underframe and values up to 0.7 MN for driver’s cab front wall;
- to place two lower-level EADs with about 2 MJ total energy absorbing capacity in the power head front end at the coupling level for protection at the identical trains collision (Scenario 1) or the train collision with freight wagon (Scenario 2). The recommended length of such EAD should be from 1.0 m to 1.5 m;
- to place two upper-level EADs with about 0.25 MJ total energy absorbing capacity in the driver’s cab window-sill part primarily for power head passive protection at the train collision with a large road vehicle on a level crossing (Scenario 3). The recommended length of the upper-level EAD should be from 0.8 m to 1.0 m;
- to place two lower-level EADs with about 0.3 MJ total energy absorbing capacity in the power head rear end part at the coupling level;
- to use box designs in the form of a truncated pyramid with cellular packages inside as lower/upper level EAD designs;
- to develop a EAD design using successful experience of EP20 locomotive EAD development and EAD prototype crash test results [17-18];
- to take into account that a driver’s cab frame shall be a power design to limit the safety zone for the driver’s survival and evacuation at accident collisions. The driver’s cab frame should have a length of at least 750 mm, withstand operating loads in accordance with DSTU EN 12663 and maximum impact loads at collisions according to the scenarios of standard DSTU EN 15227.

4. Mathematical simulation

A task of EAD design plastic deformation at collision with 80 t impactor at 36 km/h speed is considered. The scheme of interaction between the fixed EAD design (rear end EAD wall is fixed rigidly) and the moving impactor is shown in Figure 1.

The scientific methodology and mathematical models have been developed to analyze EAD designs plastic deformation at impact. Finite-element simulations have been carried out taking into account geometrical and physical nonlinearities, dynamic hardening of the steel depending on the impact speed, nonlinear contact interaction between elements of the considered mechanical system of colliding bodies. The Krieg and Kay incremental model of plasticity [19] has been used to describe the nonlinear elastic-plastic material properties under impact taking into account the kinematic hardening. This model has been 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. Modeling of nonlinear material characteristics has been based on the use of a true stretching diagram. The Simonds-Cooper dependence has been used to calculate the true dynamic yield point \([20]\). The obtained system of differential equations has been solved by the successive loading method \([21]\). As a result of the solution nodal displacements, velocities, accelerations, deformations, stresses and nodal forces at different moments of time at a given initial collision speed have been determined. The deformation diagram (dependence of the contact force \(F\) on the longitudinal displacement \(u_b\) of the impactor mass center) has been plotted using the obtained values \(u_b\) and the corresponding values of the contact force (integral over the contact area from the distributed contact stresses) between the investigated design and the impactor at the current moments. The low-pass filter with a cutoff frequency of 180 Hz \([22]\) has been used for plotting this diagram according to DSTU EN 15227.

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 (rigid vertical wall) has been simulated by solid elements with three linear displacements, velocities and accelerations at each node. This approach has previously been used and has shown good results when comparing simulation results with field test data \([17-18]\).

5. Energy absorbing devices for a power head

Lower-level EAD 1 and upper-level EAD 2 for placing in the power head front end part and lower-level EAD 3 for placing in its rear end part were developed.

EAD 1 geometric model is shown in Figure 2 (all dimensions are given in millimeters). EAD 1 design includes two elements located sequentially. Element 1 is a parallelepiped form box with a single-layer package of variable-height hexagonal honeycombs inside. Element 2 is a truncated pyramid of honeycombs with triangular cells. The thickness of the box walls is 2 mm, the thickness of the front end plate is 4 mm. The length of the hexagonal cell side is 30 mm. The thickness of plates which are forming hexagonal cells is 0.6 mm. The thickness of the truncated pyramid end plates is 8 mm. The thickness of the plates which are forming triangular cells is 2.2 mm. The thickness of the outer longitudinal ribs is 6.6 mm and their height is 2.2 mm. EAD 1 deformation diagram is shown in Figure 3.

EAD 1 design energy absorbing capacity is 0.95 MJ, its stroke is 700 mm. 1.9 MJ impact energy can be absorbed as a result of two EAD 1 deformations. The maximum contact force which is transmitted to the power head underframe is 3.0 MN not exceeding the allowed value of 4.2 MN at considered collision.

Figure 1. The scheme of interaction between the EAD and the impactor.
EAD 2 geometric model is shown in Figure 4, where all dimensions are given in millimeters. EAD 2 design has three steps in element 2 form. The possibility of placing two EAD 2 designs in a power head nose window-sill part has been taken into account. The thickness of plates which are forming the triangular cells is 2.2 mm. EAD 2 deformation diagram is shown in Figure 5.

EAD 2 energy absorbing capacity is 0.12 MJ, the stroke is 600 mm. 0.24 MJ energy can be absorbed when two EAD 2 designs are deformed at a collision with 80 t impactor at 36 km/h speed. The maximum contact force transmitted to a power head body can reach 0.66 MN not exceeding the allowed value of 0.7 MN.

EAD 3 geometric model is shown in Figure 6 (all dimensions are given in millimeters). EAD 3 design has been developed on the basis of EAD 1 design element 1. EAD 3 design is a parallelepiped form box with a four-layer package of hexagonal variable-height honeycombs placed on a diaphragm attached to the box. The thickness of the box walls, front and rear end plates, diaphragms is 2 mm. The length of the hexagonal cell side is 30 mm. The thickness of plates which are forming hexagonal cells is 0.7 mm. EAD 3 deformation diagram is shown in Figure 7.
EAD 3 geometric model.  

![Figure 6](image)

EAD 3 energy absorbing capacity is 0.3 MJ, the stroke is 300 mm. 0.6 MJ impact energy can be absorbed as a result of two EAD 3 deformations. The maximum contact force transmitted to the power head underframe is 2.6 MN not exceeding the allowed value of 3.0 MN for a coach underframe. It has been recommended to place two EAD 3 in the inter-car connection at the coupling level.

### 6. Conclusion

Proposals on domestic power head passive protection at collisions according to DSTU EN 15227 requirements were developed on the base of existing passive safety systems analysis. 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. Finite-element modeling of plastic deformation of EAD designs which contain cellular elements at impact has been carried out with the using of developed scientific and methodological support and the results of the crash test of the EP20 locomotive EAD prototype. As a result of it the EAD 1, EAD 2, EAD 3 designs have been developed.

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. 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 developed scientific methodology and mathematical models can be used to select the parameters of energy absorbing devices with the required energy absorbing capacity to carry out the collision scenarios according to DSTU EN 15227 on the stage of the new-generation passenger rolling stock design.

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