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PASSIVE SAFETY OF HIGH-SPEED PASSENGER TRAINS AT ACCIDENT COLLISIONS ON 1520 MM GAUGE RAILWAYS

Summary. The fundamental principles of the passive protection concept of high-speed passenger trains at accident collisions on 1520 mm gauge railways have been developed. The scientific methodology and mathematical models for the analysis of plastic deformation of cab frame elements and energy-absorbing devices (EAD) at an impact have been developed. The cab frame and EAD for a new-generation locomotive have been designed. The EAD prototype crash test has been carried out.

1. INTRODUCTION

One of the main directions of the railway transport development in Ukraine is the application of high-speed passenger traffic and the implementation of a new-generation rolling stock with the effective active protection to prevent collisions and passive safety systems operating automatically in the case of an accident collision and permitting to reduce the consequences of heavy accident collisions and to save human lives. Similar problems are common for all countries of the former Soviet Union.

In EU countries, passive safety assurance of high-speed train railway vehicles is mandatory and, since 2008, is regulated by EN 15227 [1]. In Ukraine, requirements regulating the passive safety of rolling stock are still missed. However, current tendencies of Ukrainian railway transport development are increase of train speeds, orientation toward European integration and European standards and the need to upgrade the rolling stock. Standard EN 15227 has become a powerful stimulus and example for the normative basis development in the CIS countries. At present, vehicles' passive safety problems for the 1520 mm gauge railways are being actively worked out. In 2010 and 2011, in the Russian Federation, "Specifications for Passive Safety System of Rolling Stock for Passenger Traffic on Railways with 1520 mm Gauge" [2, 3] have been implemented. In 2014, the Russian Federation issued the interstate standard "Emergency crash-systems railway rolling stock for passenger transportations. Technical requirements and methods of control" [4]. Its key distinctive feature is that it takes into account the significant differences in railway rolling stock designs and accident collision statistics on the CIS and EU railways. However, this standard is not equivalent to EN 15227 and serves as a guideline.

Nowadays, the passive protection of the majority of European locomotive-hauled passenger trains equipped with separate draw-and-buffer gear devices is arranged in the following way. The crash buffer and lower level energy-absorbing devices placed on them at the locomotive's front end absorb the main part of the energy on collisions with railway rolling stock [5-10]. Intermediate coaches of passenger trains are usually equipped only with crash buffers [9, 10].

An analysis of existing passive protection devices for passenger locomotives and head coaches with combined draw-and-buffer gear devices has been carried out. It has been established that such protection includes push-back automatic couplers, multi-level EAD systems and crumple zones in the end parts of all intermediate coaches [11-15].

The passive protection of passenger electric and diesel trains is organized in the following way. The energy-absorbing devices of the head coach absorb the main part of the accident collision energy [16-18]. The front end of the head coach is equipped with a lightweight push-back automatic coupler and a multi-level system of energy-absorbing devices usually placed outside the driver's cab. The intermediate coaches are also equipped with couplers and anti-climb units usually including energy-absorbing components.

The traditional rolling stock for 1520 mm gauge railways has a number of significant distinctions (in the draw-and-buffer gear devices, regulatory requirements for its development, etc.) compared with European rolling stock with effective passive safety systems. The main problem is the SA-3 automatic coupler device. Its design and fastening to the locomotive underframe enable provision of a passive safety system with energy-absorbing elements that work during accidents. The SA-3 automatic coupler device transmits longitudinal impact loading to the underframes of the electric locomotive and coaches behind it. Development of a new-generation rolling stock with a passive safety system for 1520 mm gauge railways should be based on engineering solutions scientifically proven by investigations of the stress–strain state (SSS) of railway vehicle design elements under standard quasi-static loads and at impacts arising on accidental collisions.

The railway vehicles' safety problem is an actual problem worldwide [5-18]. Germany, France, Japan and the USA are leaders in this problem solving. In European countries, theoretical and experimental researches on the passive protection of railway rolling stock were actively carried out from the early 1990s. Substantial contribution toward solving the problem of railway vehicles' passive protection has been made by experts from Alstom, Bombardier Transportation, Dellner, Siemens, Voith Turbo, PESA and a number of other scientific and manufacturing enterprises.

At present, for countries with 1520 mm gauge railways, it is necessary to develop techniques to evaluate vehicle design elements, SSS, taking into account plastic deformations of passive safety system elements at impacts using mathematical simulations. The actual problems are in defining the main requirements for passenger train passive safety at accident collisions, to develop a scientific methodology and mathematical models to analyze deformations of railway vehicles with a passive safety system at impacts, to carry out appropriate research and to design a new-generation rolling stock based on the results obtained.

2. FUNDAMENTAL PRINCIPLES OF THE PASSIVE PROTECTION CONCEPT

Following the study of global experience reviews of the passive safety of passenger trains at accident collisions [5-21] and regulatory requirements on this problem [1-4], the fundamental principles of the passive protection concept of high-speed passenger trains for 1520 mm gauge railways have been developed. According to the proposed concept, the passive safety systems should be included in the architecture of the rolling stock and integrated into the structure of all vehicles for newly designed passenger trains.

The train passive safety system elements include obstacle deflectors at the frontal parts of locomotives and head coaches, push-back automatic couplers, anti-climbers, energy-absorbing devices, crumple zones at the end parts of vehicles, safety zones and other engineering solutions to reduce risks for passengers and train crew at accident collisions.

The requirements for vehicle static strength and passive safety at accident collisions on 1520 mm gauge railways should be harmonized with the requirements of the relevant European standards EN 12663 [22] and EN 15227 [1].

The passive safety system should protect passengers and a train crew in most probable accident collisions. We have analyzed the statistics of real accident collisions on the CIS and EU railways. We have also compared the collision scenarios according to [1] and [4]. As a result, we believe that collision scenarios [1] more adequately characterize most probable collisions on both 1520 mm and 1435 mm gauge railways. However, obstacles models in the collision scenarios of a new Ukrainian standard (analog EN 15227) should be developed taking into account the push-back automatic couplers.

3. DEVELOPMENT OF THE LOCOMOTIVE DRIVER'S CAB WITH PASSIVE SAFETY SYSTEM ELEMENTS

The first step toward radically new motive power was the development of the EP20 mainline electric locomotive (Fig. 1) based on a number of innovative engineering solutions and adopted locomotive passive safety requirements.

Fig. 1. High-speed passenger electric locomotive EP20

Today, the EP20 is the world's most powerful (7,200 kW) single-unit six-axle passenger electric locomotive with dual power supply. The EP20 electric locomotive is the first in a series of fifth-generation electric locomotives for railways with 1520 mm gauge. The EP20 constructive platform is intended to be the basis for the development of different series of passenger and freight locomotives. Some components for the EP20 electric locomotive, in particular, the modular driver's cab and passive safety system crash elements, were designed and manufactured in Ukraine by "MDC Research-and-Development Manufacturing Enterprise" Limited Liability Company with the participation of the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine.

The requirements for passive safety of the new-generation locomotive have been designed according to [2, 3] and the requirements specification for its development:

– the electric locomotive should be equipped with draw-and-buffer gear devices that do not create obstacles for the passive safety system work at accident collisions;

– the electric locomotive underframe design should allow the passive safety system elements to operate adequately without loss of its total bearing capacity in the basic collision scenarios;

– most of the energy should be absorbed due to the plastic deformation of energy-absorbing devices at the end parts of the locomotive underframe;

– the essentially new cab frame design should include such passive safety system elements as a strengthened anti-penetration front wall, a crumple zone, a safety zone for the survival and evacuation of the locomotive crew;

– the metal cab frame should have a load-bearing belt below the front window and be able to withstand a static load of 290 kN uniformly distributed across the width of the front wall;

– the crash elements and the crumple zone of the cab are to be destroyed first at accident collisions;

– about 2 MJ of kinetic energy should be absorbed as a result of the plastic deformation of passive safety system elements in an accident without exceeding the allowable 5 g level of longitudinal decelerations in the driver's cab safety zone (not less than 750 mm in length).

According to the above-mentioned requirements for locomotive passive safety, a design layout scheme of the driver's cab frame with energy-absorbing devices has been designed (Fig. 2).

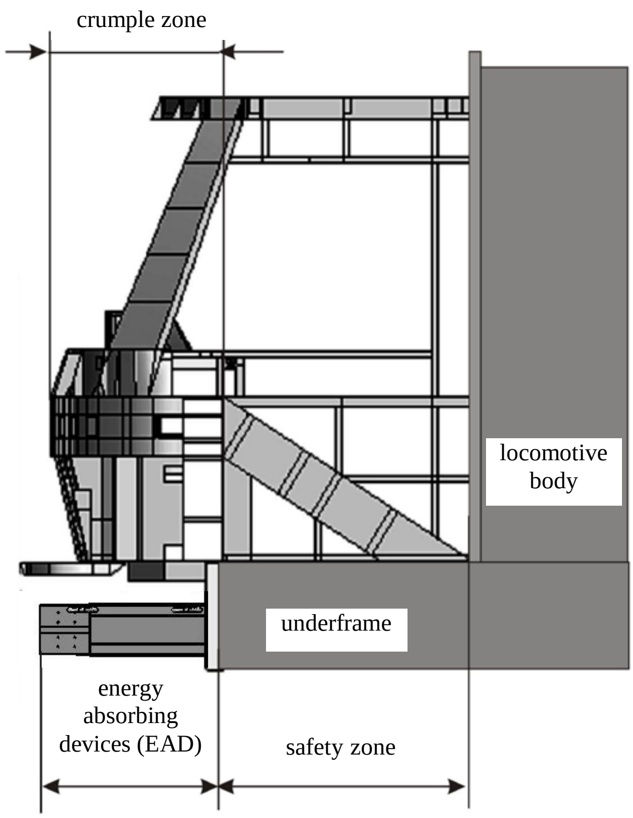

Fig. 2. Design layout scheme of the driver's cab frame with energy-absorbing devices

4. MATHEMATICAL SIMULATION

Mathematical simulation of plastic deformation of the locomotive front part elements under the longitudinal impact loading according to the collision scenarios has been carried out using the finite-element method.

When developing the EP20 electric locomotive passive safety requirements, two collision scenarios [3] were considered. A rigid vertical wall was considered as an obstacle (an impactor) in the scenarios.

Scenario 1: the collision of an electric locomotive at a speed of 72 km/h with a 10 t non-deformable obstacle on a track crossing;

Scenario 2: the collision of an electric locomotive at a speed of 36 km/h with an 80 t freight wagon.

The scientific methodology and mathematical models have been developed to analyze the stress–strain state of the driver's cab design elements and energy-absorbing devices under impact loads due to accident collisions. The scientific methodology includes a computer engineering three-dimensional geometric studied design model by SolidWorks [23], import of the geometric model into the program ANSYS LS-DYNA [24, 25] to solve the dynamical problem by the finite-element method (FEM), development and testing of a mathematical model to study design plastic deformations at impact, performing calculations and plotting diagrams (dependencies of a contact force F and an energy E on the longitudinal impactor mass center displacement u_b).

Finite-element simulations have been carried out taking into account geometrical and physical nonlinearities, dynamic hardening of the steel depending on the impact speed and the nonlinear contact interaction between elements of the considered mechanical system of colliding bodies.

The von Mises yield criterion accounting for the influence of the loading rate on the physical and mechanical properties of materials [26] has been used for the determination of plastic deformation appearance. The Krieg and Kay incremental model of plasticity [25, 27] has been used to describe the nonlinear elastic-plastic material properties under impact. This model, accounting for the kinematic hardening, has been based on the bilinear approximation of the true stress–strain diagram. An inflection point of the bilinear approximation line corresponds to the true dynamic yield strength s_d, which depends on the strain rate. The Symonds–Cooper relationship [28, 29] has been used to calculate s_d.

The differential equation system of the mechanical system motion in increments is as follows:

$$M\Delta\ddot{U} + K_c(\sigma,U)\Delta U = \Delta Q\,, \tag{1}$$

where M is the matrix of mass; $K_c(\sigma,U)$ is the stiffness matrix taking into account the geometric and physical nonlinearities; ΔU is a vector of displacement increment; and ΔQ is a vector of load increment.

System (1) is solved by the successive loading method [30]. Nodal displacements, velocities, accelerations, displacements, the stress–strain state of finite-element system elements, nodal forces and a contact force F (an integral of contact stresses at a contact area) between the impactor and the studied design at the current time are determined as a result of the solution.

The low-pass filter with a cut-off frequency of 180 Hz [31] is used to plot diagrams according to the requirements of EN 15227 [1].

The finite-element mathematical models for the nonlinear dynamic stress–strain state analysis of the energy-absorbing device and driver's cab frame elements under impact loading 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.

5. DRIVER'S CAB FRAME AND ENERGY-ABSORBING DEVICES FOR LOCOMOTIVE

Using the above-mentioned scientific methodology and the finite-element mathematical models developed, the stress–strain state of structural elements of the EP20 locomotive front part including the driver's cab frame with the control desk and two crash elements under the static load of 290 kN and at impacts by the rigid vertical wall according to the collision scenarios was investigated [8, 32]. The frame material is 09G2S steel. As a result of the investigations, the driver's cab frame design corresponding to the current operational requirements and the requirements for passive safety of the new-generation locomotive is shown in Fig. 3.

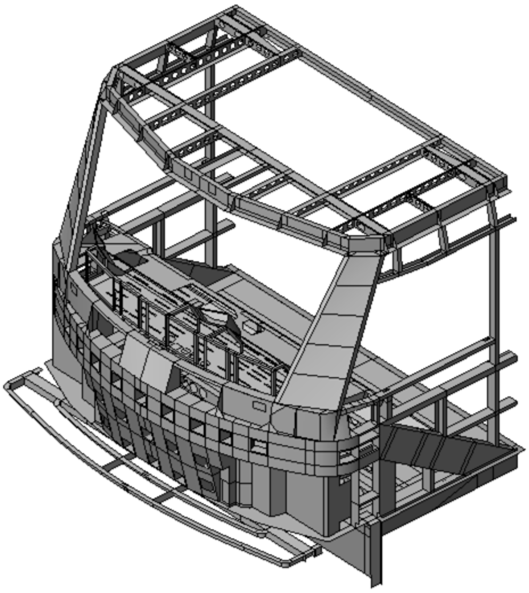

Fig. 3. The driver’s frame cab design for the locomotive with a passive safety system

As a result of the complex theoretical research carried out, a box-type energy-absorbing device design containing steel honeycomb blocs (Fig. 4-5) has been developed and patented [8, 32, 33]. The energy-absorbing devices are intended to be placed at the end parts of the locomotive underframe. The parameters of the EAD design with a 1.1 MJ energy-absorbing capacity have been determined.

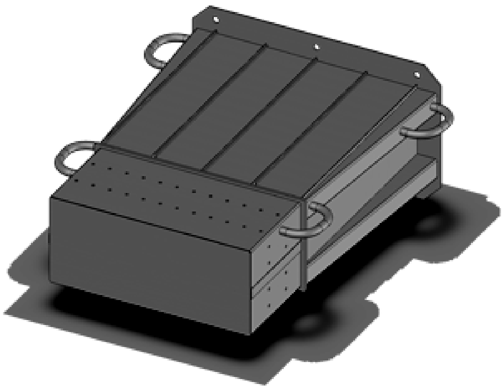

Fig. 4. EAD for locomotive

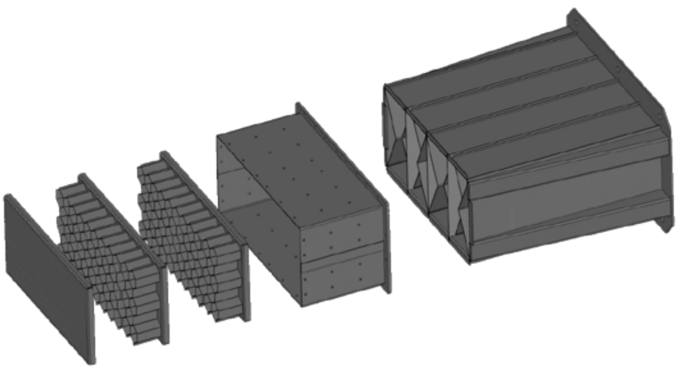

Fig. 5. EAD design elements

6. EAD CRASH TEST AND ITS MATHEMATICAL SIMULATION

A crash test of the developed energy absorbing device prototype has been performed at the TÜV SÜD Rail GmbH rolling stock test center (Gorlitz, Germany) (Fig. 6).

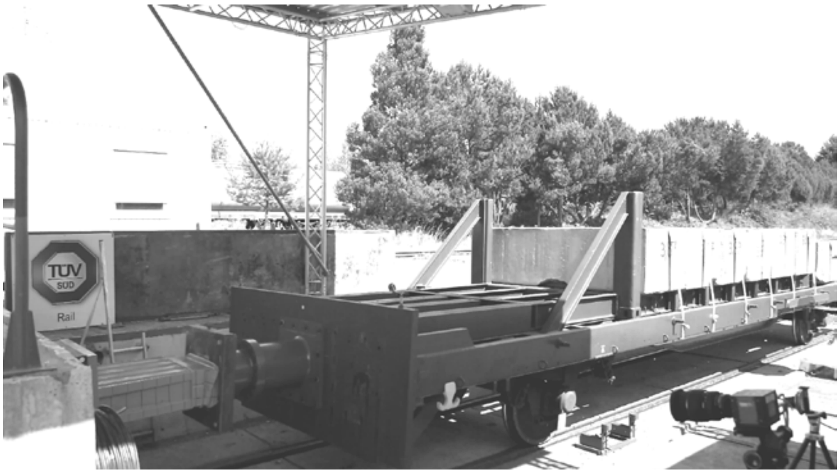

Fig. 6. Crash test of the energy-absorbing device prototype

Almost all European firms that produce rolling stock, crash buffers and other passive protection elements use TÜV SÜD Rail GmbH rolling stock test services for crash tests.

The TÜV SÜD Rail GmbH rolling stock test center has carried out the crash test EAD prototype using the test stand. It includes a straight section of railway and a 200 m concrete block at the end. A steel plate with a force-measuring unit was installed on the concrete block. The EAD prototype was mounted on this plate. A station for management and processing of test results was located near the stand. In the tests, we used four 1200 kN power sensors (RF series, made by GTM company in Germany), high-speed and usual video cameras, and velocity and displacement sensors. A wagon-impactor is a platform with a corresponding mass cargo. For the crash test, the mass of the wagon-impactor was 40.6 m; the speed at impact was 24.7 km/h.

The EAD prototype and the energy-absorbing device for the EP20 locomotive had differences in geometrical parameters, but they were composed of the same material of 08U steel.

The mathematical simulation of elastic–plastic deformation of the energy-absorbing device prototype design at an impact by a wagon-impactor (its mass is M = 40.6 t, speed is V = 24.7 km/h) in accordance with the crash test conditions has been carried out on the bases of the developed scientific methodology and finite-element mathematical models (see subheading 3). The scheme of interaction between the EAD and the wagon-impactor is shown in Fig. 7.

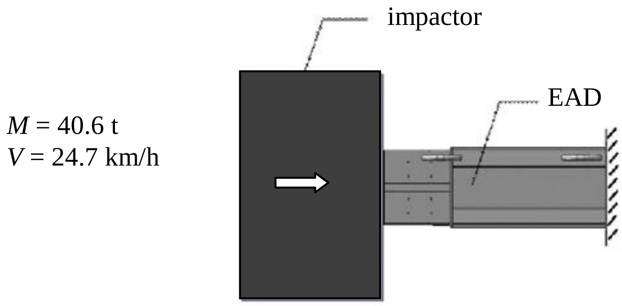

Fig. 7. The scheme of interaction between the EAD and the wagon-impactor

7. RESULTS

The crash test fragments and finite-element simulation results for various values of a wagon-impactor displacement u_b are represented in Fig. 8.

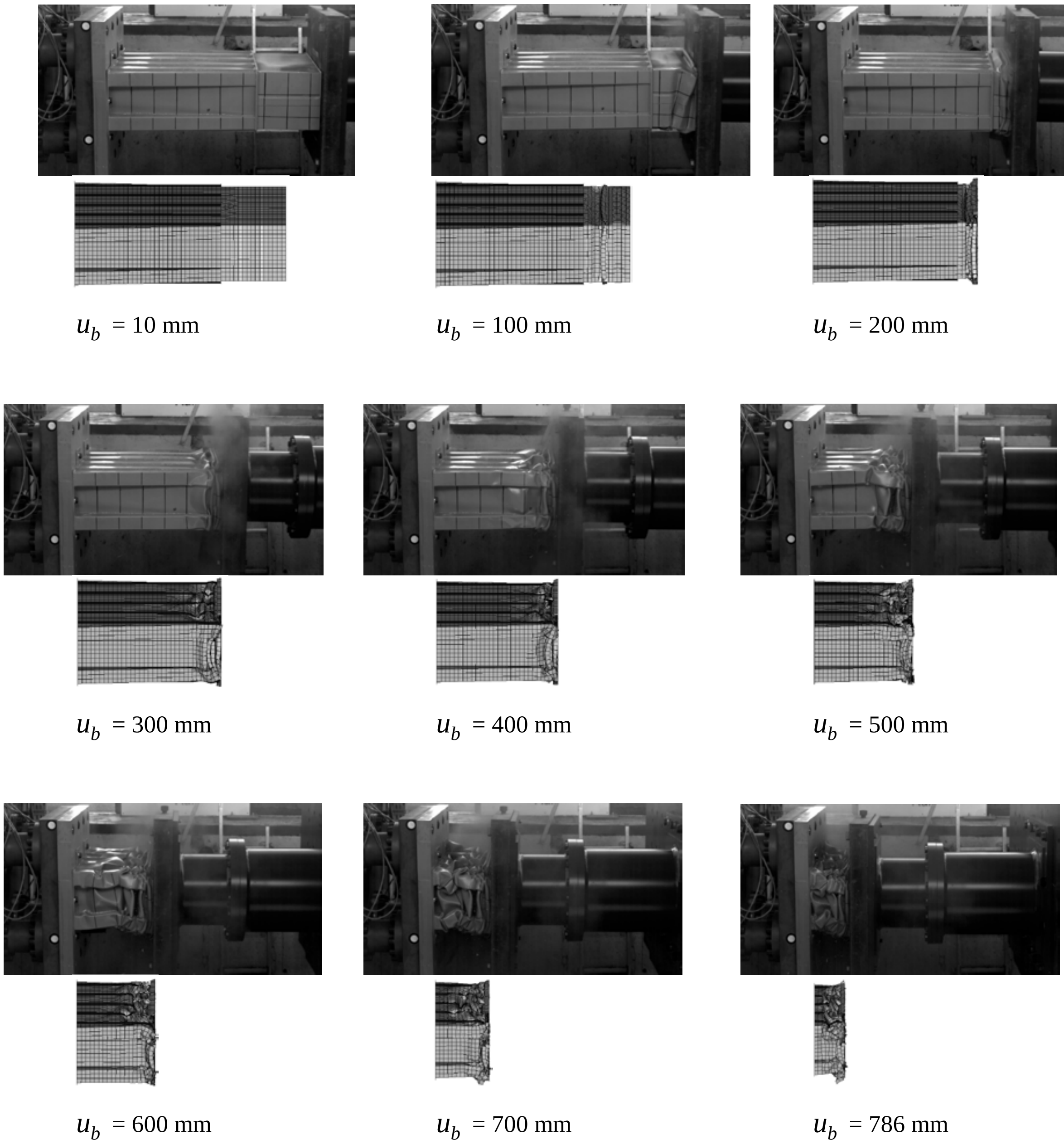

Fig. 8. Crash test fragments and finite-element simulation results

A comparison of the calculated and experimental diagrams (Fig. 9-10) has been made on the energy-absorbing device working stroke interval ($0 \le u_b \le 700$ mm) of the EAD prototype design according to the criteria of the European standard EN 15227 [1].

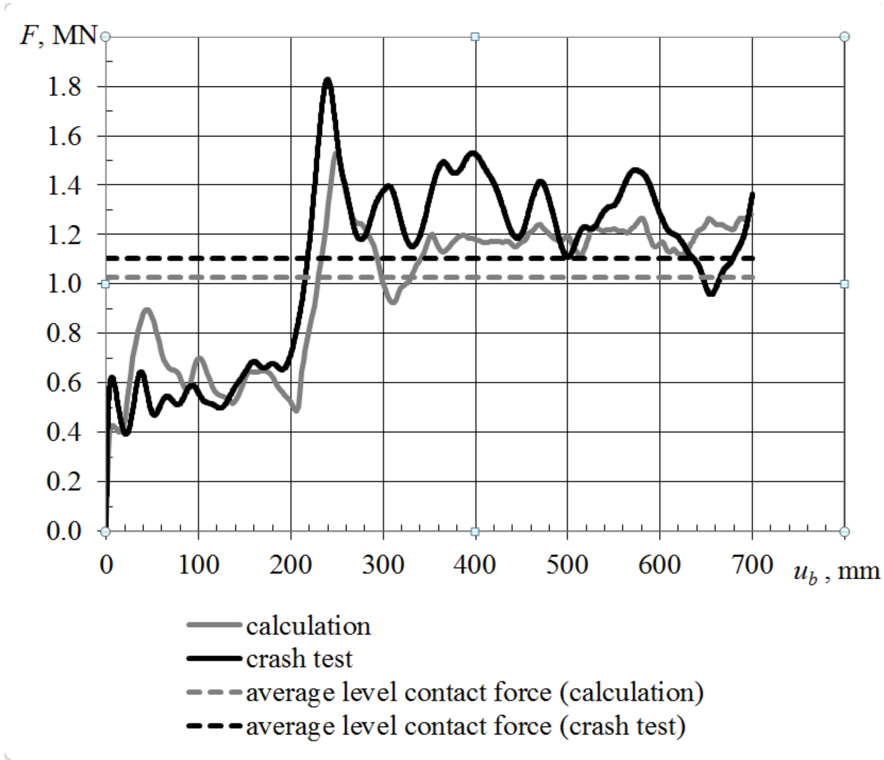

Fig. 9. The calculated and experimental dependencies of a contact force F on the displacement u_b

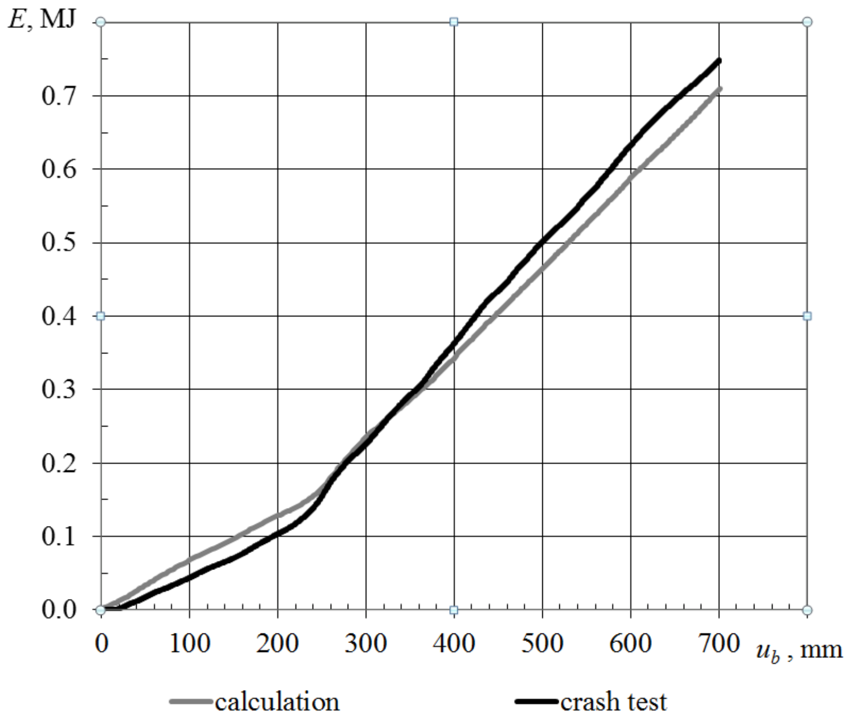

Fig. 10. The calculated and experimental dependencies of an absorbed energy E on the displacement u_b

It has been established that the difference between the average values of the contact force F between the wagon-impactor and the EAD prototype is 7% (the acceptable deviation is 10%). The divergence of the theoretical and experimental values of the absorbed energy E for u_b = 700 mm is 5% (the acceptable deviation is 10%). The good concurrence of the theoretical and experimental values of the contact force and the absorbed energy confirm the reliability of finite-element simulation results and the potential usefulness of the developed scientific methodology and mathematical models.

8. CONCLUSION

The fundamental principles of the passive protection concept of high-speed passenger trains for 1520 mm gauge railways at accident collisions have been developed. The scientific methodology and mathematical models have been developed for the mathematical simulation of plastic deformation of the locomotive front part elements including the driver’s cab frame and energy-absorbing devices under the longitudinal impact. The driver’s cab frame and energy-absorbing device for the new-generation locomotive have been designed. A crash test of the energy absorbing device prototype has been carried out. As a result of the complex of theoretical and experimental investigations, the modular driver’s cab for a high-speed passenger locomotive with a passive safety system has been designed, manufactured and put into production.

The scientific methodology and mathematical models developed 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 EN 15227 in the new-generation passenger rolling stock design.

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