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EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE CHARACTERISTICS OF COMBINED COLLISION ENERGY ABSORBERS

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Abstract. *The subject of this paper are experimental researches and numerical simulations of combined collision energy absorber. These elements are parts of passive safety measures of railway vehicles. This type of absorber works on the principle of controlled deformation using shrinking and folding process of the tubes. The idea was to use process of shrinking and folding tubes in a parallel mode to absorb as much collision kinetic energy as possible by controlled deformation, with limited dimensions of absorber. Energy absorption was achieved by elastic-plastic deformations of the tubes and friction between the tube and the cone bush. Using combined method, during the collision, energy absorption starts in the tube which is compressed into cone bush. After pre-defined stroke in the process of energy absorption the simultaneous process of folding of the outer tube starts, so both tubes deform in parallel mode during the rest of the stroke. In this way the force gradually increases without undesirable peaks during the entire stroke, resulting significant bigger amount of absorbed energy. Experimental investigations of combined absorber were realized in laboratory conditions. During experimental investigations the stroke and force were measured. The numerical simulations were used for checking the absorption power of absorption elements before the experimental researches. After the numerical simulations and quasi-static tests were completed, recorded data were analyzed and force versus stroke diagrams were made. Results of calculation using FEM and results obtained experimentally are in good correlation.*

Key Words: *Experimental Researches, Combined Absorber, Railway Vehicles, Passive Safety*

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1. INTRODUCTION

This paper presents results of numerical simulations and experimental investigations of combined tube collision kinetic energy absorber. These elements are part of passive protection measures of the railway vehicles. This type of absorber works on the principle of shrinking and folding the tubes. The idea to combine these two processes of deformations, stemmed from the need to increase the absorption power and to reduce the space required for installation, which is in the frontal part of the wagon very limited. The reason for analyzing this type of elements is further increase of the protection level of the wagon structure behind the absorbers, thus to increase safety of passengers, goods and railway vehicles. By using this type of absorber, energy absorption occurs by elastic-plastic deformations of the tubes and friction between the tube and the cone bush. The combined method was chosen for two reasons: first, tube shrinking absorber has very good characteristics [1], and second, to exclude very high values of the force (peak) on the deformation start, which characterize folding of the tube absorber [2]. Fig. 1 shows the look of the combined absorber with characteristic dimensions before start the investigations (undeformed absorber). During the collision, absorption of the energy starts in the inner tube (Item 1) which compresses into cone bush (Item 3). After pre-defined stroke, the process of deformation of the outer tube starts and on the rest of the stroke both tubes (Item 1 and Item 2) absorb collision energy in parallel mode.

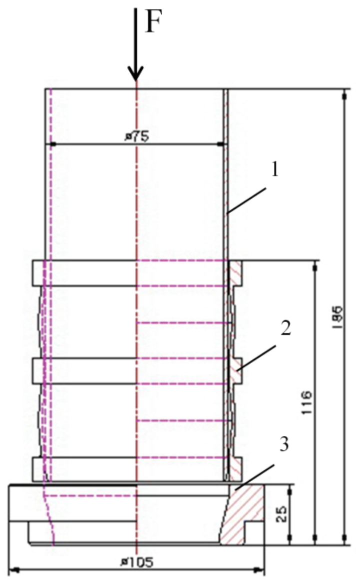

Fig. 1 Combined absorber

The force gradually increases using this method, without undesirable peaks during the entire stroke, resulting in a significant bigger amount of absorbed energy. During development of absorption elements couple, the results of experimental investigations given in [3], [4] and [5] were used. This paper analyzes influence of strain-rate on the deformation resistance and grooves effects on crashworthiness characteristics of thin-walled conical tubes.

Research in this field is significant for the design of railway vehicles. Moreover, according to the OTIF (former RID) regulations and new UIC Leaflet No. 573 on tank wagons for transporting hazardous materials (toxic materials and flammable gasses: 2T and 2F) buffers capable of absorbing collision energy must be installed by the end of 2012. For new railway vehicles (manufactured from 2007) each buffer must absorb 400 kJ of energy, and 250 kJ for railway vehicles already in use [6].

This paper analyzes influence of strain-rate on the deformation resistance and also presents experimental investigations based on quasi-static test. During investigations the force and stroke were measured. Prior the experimental investigations, designed characteristics of absorption couple were checked using numerical simulations. After the tests completion, recorded data were analyzed and compared with results obtained using numerical analysis.

2. Numerical Simulations

Numerical simulation was performed using software package ANSYS. Considering working principle of combined absorber, numerical model was formed using the following elements: plane seamless tube (Item 1) with dimensions ∅75x2x160mm from structural steel S355J2G3, segments tube (Item 2) with dimensions ∅86/76x2x90mm from structural steel S355J2G3 and the cone bush (Item 3) with dimensions ∅105/68x13º from quenched and tempered carbon steel C45E, Fig. 1.

Using the finite elements method (FEM), the nonlinear numerical simulation on the plane axisymmetric model (Fig. 2), using Perzyna material model with rate dependent options was realized [3]. Areas A1, A2 and A3 represent different elements of the model.

Rate-dependent visco-plasticity describes the flow rule of materials, which depends on time. The deformation of materials is assumed to develop as a function of the strain rate (or time). A typical application of this material model is the simulation of material deformation at high strain rates, such as impact.

Perzyna model has the following form [7]:

$$\sigma = \left[1 + \left(\frac{\dot{\varepsilon}^{pl}}{\gamma}\right)^m\right]\sigma_0 \qquad (1)$$

Where are: σ - Material yield stress, $\dot{\varepsilon}^{pl}$ - Equivalent plastic strain rate, m - Strain rate hardening parameter, γ - Material viscosity parameter, σ_0 - Static yield stress of material.

The key parameters which define a rate-depending option for this type of analysis are m and γ. Note that σ_0 is a function of some hardening parameters in gen-

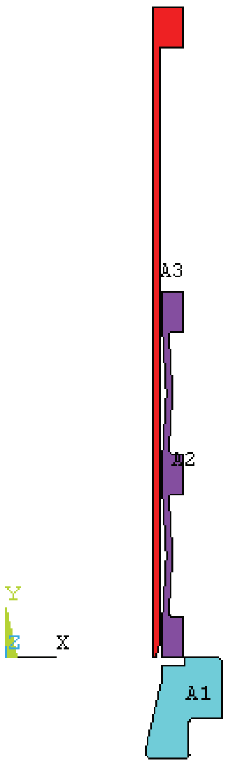

Fig. 2 Plane axisymmetric model

eral. As γ tends to ∞, or m tends to zero or ε_{pl} tends to zero, the solution converges to the static (rate-independent) solution.

Numerical simulations were realized using PLANE 42 elements. This type of element is used for 2-D modeling of solid structures. Element can be used either as a plane element (plane stress or plane strain) or as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

Most common engineering materials exhibit a linear stress-strain relationship up to a stress level known as the proportional limit. Beyond this limit, the stress-strain relationship will become nonlinear, but will not necessarily become inelastic. Plastic behavior, characterized by no recoverable strain, begins when stress exceed the material's yield point. In accordance with previous for these calculations multilinear characteristic of material is used. This option is often preferred for large strain analysis.

Having in mind 2D models included in these calculations, the contact surface to the surface element is used. For quasi-static simulations, values for key parameters are following: m=0,403 and γ=305, [3].

3. Experimental Investigations

Experimental investigations were performed under laboratory conditions on a servo-hydraulic machine ZWICK ROELL HB250, at the Faculty of Mechanical Engineering in Belgrade, Fig. 3, with maximum compression force equal to 250 kN. Machine is property of Laboratory for testing of machine elements and systems and it is donation of Ministry for Education, Science and Technological Development of the Republic of Serbia.

The HB250 testing machine consists of the test frame, test actuator, travel measurement system and control unit, as well as the hydraulic power pack, Fig. 3.

The electronics can record up to 8 measurement channels per actuator, with data acquisition frequency up to 10 kHz.

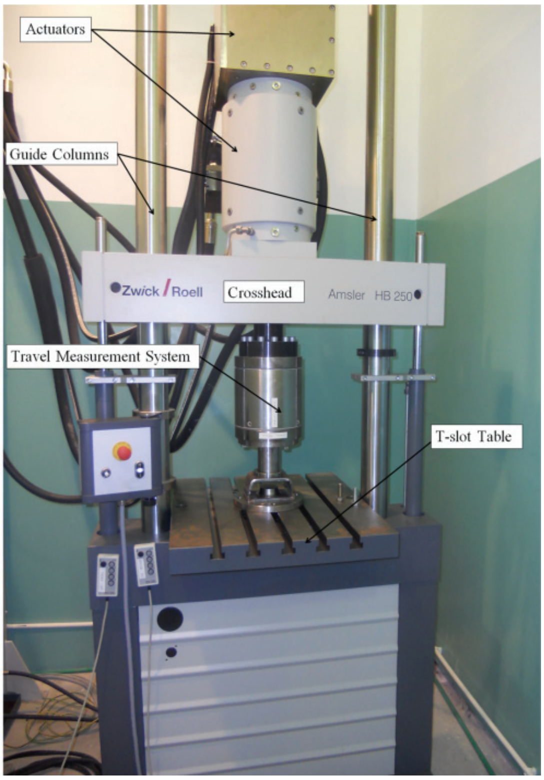

Fig. 3 Servo-hydraulic machine ZWICK ROELL HB250

3.1. Working principle

Working principle of combined absorber can be described using Fig. 1. This figure shows combined absorber in the testing machine before start of deformation process. Combined absorber works on the principle of compressing and folding tubes at the same time. During collision, process of energy absorption first starts with the tube shrinking (Item 1) during stroke of ≈ 63 mm. After the stroke of 63 mm, second mode of energy absorption i.e. folding of the tube starts (Item 2). In that moment, energy absorption continues in parallel working mode, compressing and folding tubes on the stroke of 40 mm (Items 1 and 2). Combined principle was chosen to decrease undesirable peaks of the force at the start, which characterize the folding process. The combined process of energy absorption gives significant lower values of the force peaks at the start of the folding process and at the same time, for the same amount of absorbed energy requires lower thickness, comparing to absorber using only folding tube process. Experimental investigations were realized in two phases. First phase served for selection of the most appropriate design of the folding tube between several designs. In the second phase extensive investigations of complete absorber were performed and piston speed influence was analyzed.

3.2. Samples

The following elements were used for this investigation: seamless tubes (Item 1, 2, 3 and 4) from structural steel (material S355J2G3) and the cone bush (Item 5) from quenched and tempered carbon steel (material C45E), Fig. 4.

Samples in Fig. 4 are separated in five groups: a) seamless tubes with two folding segments with cone walls (Item 1), b) seamless tubes with two folding segments with plane walls (Item 2), c) plane seamless tubes of length L = 160 mm (Item 3), d) plane seamless tubes of length L = 71 mm (Item 4) and e) cone bush (Item 5). Different geometries of the folding tubes are created to show influence of the wall geometry on the start values of the deformation resistance.

Fig. 4 Samples of absorption elements

3.3. Quasi-Static Tests – Phase I

In the first phase of the test, force vs. stroke, characteristics F(h) were recorded during the process of folding tube segment with plane and cone wall. During research force and stroke were measured at the speed of machine piston of 0,17 mm/s. Fig. 5 shows sample before (left) and after (right) the process of deformation.

Fig. 5 Quasi-static tests – Phase I

As expected, tube consisting of segments with coned wall (Fig. 4, Item 1) showed better characteristics, more appropriate for the combined process of energy absorption. Geometry of the tube with cone wall allows predicting the deformation starting position (peak of the cone). This geometry shows lower values of the force at the start of the folding process what was one of the aims of this paper.

3.4. Quasi-Static Tests – Phase II

In the second phase of research F(h) characteristics of the complete combined absorber were recorded. Assembly was formed of inner plane seamless tube and outer segment tube with cone wall. During research force and stroke were measured. Tests were performed at two speeds of machine piston 0,17 mm/s and 25 mm/s. Fig. 6 shows absorber before (left) and after (right) the process of deformation.

Fig. 6 Quasi static tests – Phase II

After these tests, as expected, different values of the force for two different piston speeds were obtained. In this way, the influence of the strain rate on the values of deformation resistance was considered. This means that higher values of piston speeds give higher values of the deformations resistance and vice versa.

4. RESULTS

4.1. Results of numerical simulations

After the numerical simulations were completed, the recorded data were analyzed and force versus stroke diagram is shown in Fig. 7.

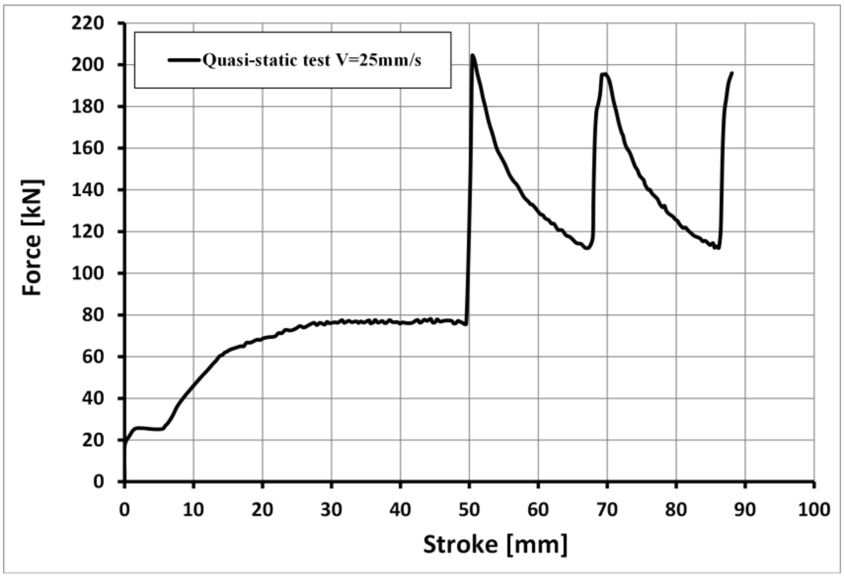

Fig. 7 Force vs. stroke diagram – Numerical simulation

This diagram characterizes two clearly separated phases. First phase, when the stroke is approximately 50 mm, shows process of shrinking the inner tube. Second phase shows shrinking and folding tubes in parallel mode on the rest of stroke (from 50 mm up to the end of the absorption process). Characteristic peaks in the second phase are the consequence of the folding process. Number of peaks shows number of segments of the outer tube.

Fig. 8 shows shape of the combined absorber after deformation process. Different colors show levels of displacement of the elements (plane and segment tubes) along the "Y" axis.

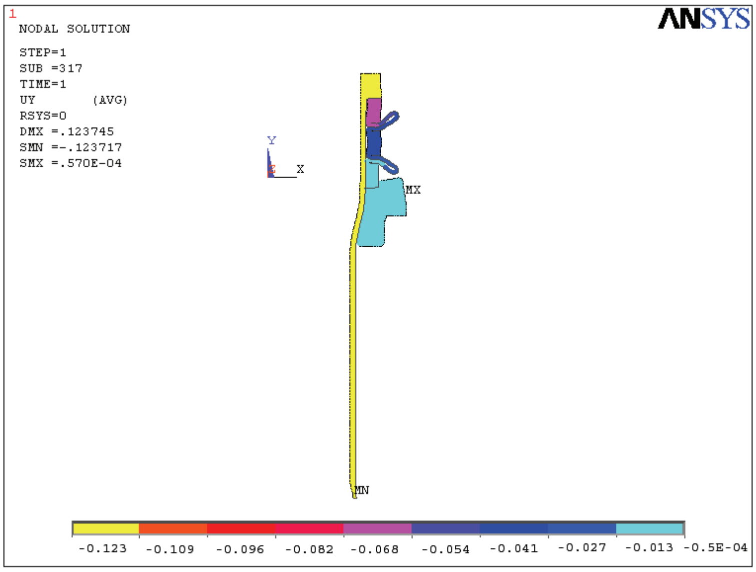

Fig. 8 Combined absorber after deformation process – Displacement [m]

4.2. Results of experimental investigations

Quasi-Static Tests – Phase I. Fig. 9 shows force versus stroke diagram obtained in the first phase of experimental investigations, for tube with two folding segments with plane walls.

Fig. 10 shows force versus stroke diagram obtained at the same phase for tube with two folding segments with cone wall.

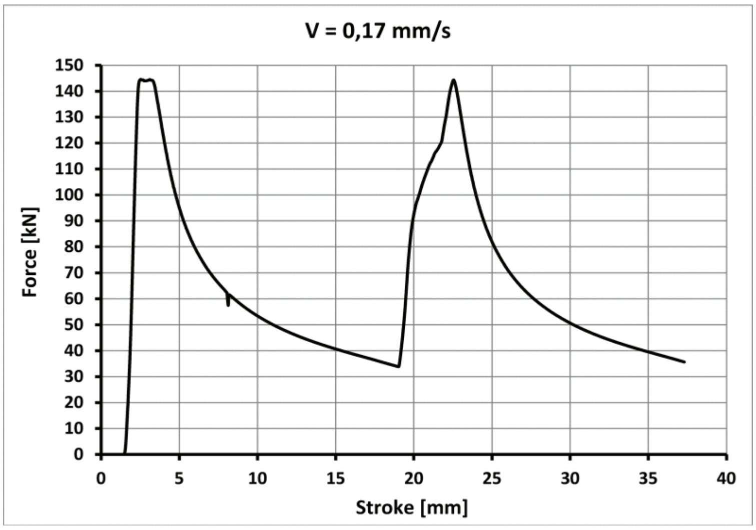

Fig. 9 Force vs. stroke diagram – plane wall tube

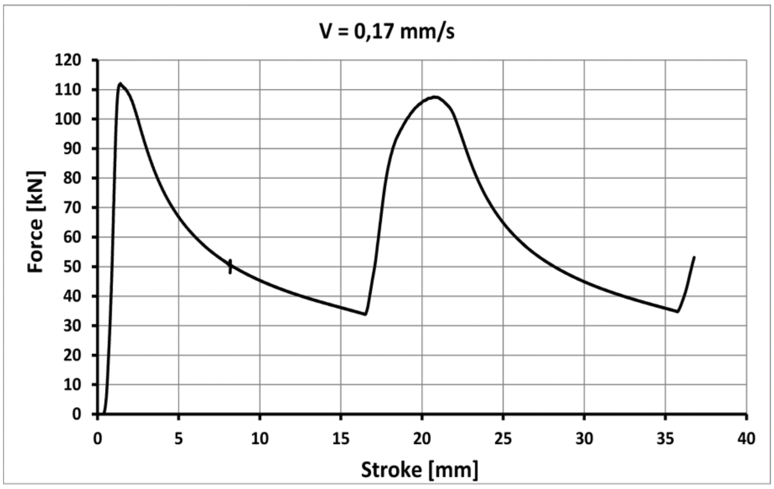

Fig. 10 Force vs. stroke diagram – cone wall tube

Both diagrams show the expected characteristics for the folding process of the tubes. The highest value of the force was at the deformation start, when force reached 145 kN for the tube with plane wall and 110 kN for the tube with cone wall. At this moment tube lost stability and force started to decrease until the beginning of the second segment folding, when the force again started to increase. Force flow is a jagged flow and number of maximum values (peaks) equals the number of segments of the tube. As expected, tube with cone wall has a better characteristic, more appropriate for the combined process of energy absorption. Geometry of the tube with cone wall allows predicting the deformation starting position (peak of the cone). As shown in the previous diagrams, this geometry shows lower values of the force at the start of the folding process. According to above mentioned, two segments tubes with cone wall were chosen for the second phase of the quasi-static investigations.

Results of Quasi-Static Tests – Phase II. Tests were realized for two different values of the piston speed with exactly defined values of the piston stroke. Fig. 11 shows force versus stroke diagram obtained during second phase at the piston speed of 0,17 mm/s.

This diagram is characterized by two clearly separated phases. The first phase is shrinking of the tube into a cone bush at stroke of approximately 60 mm. Second phase is parallel action of the shrinking tube and the folding tube at the stroke length of approximately 35 mm.

Fig. 12 shows force versus stroke diagram obtained during investigations at the piston speed of 25 mm/s. Curve in this diagram has the same character as the curve in the previous diagram (Fig. 11). Main difference between two diagrams is different value of the forces, which is higher in case of higher value of the strain-rate (Fig. 12).

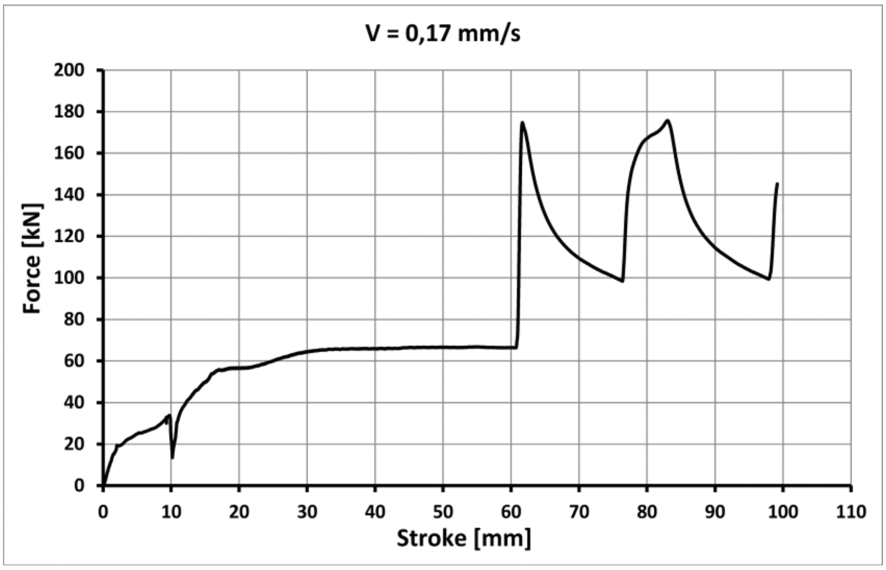

Fig. 11 Force vs. stroke diagram – combined absorber (V=0,17mm/s)

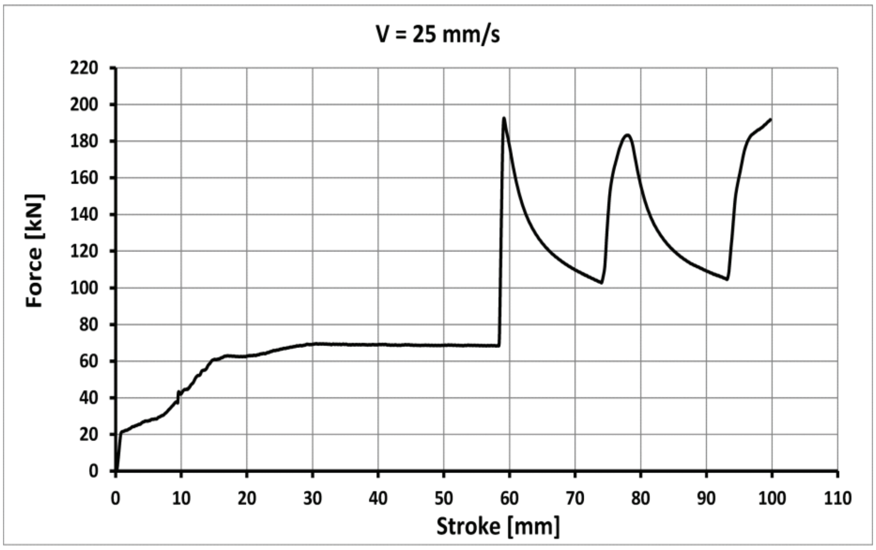

Fig. 12 Force vs. stroke diagram – combined absorber (V=25 mm/s)

To achieve better overview of the results and their relations, Fig. 13 shows both curves obtained by numerical simulations and experimental investigations. In this diagram can be clearly seen that numerical and experimental results are in good correlations. Differences in stroke values between curves are caused by difference in defined stroke of the first phase characterized by tube shrinking.

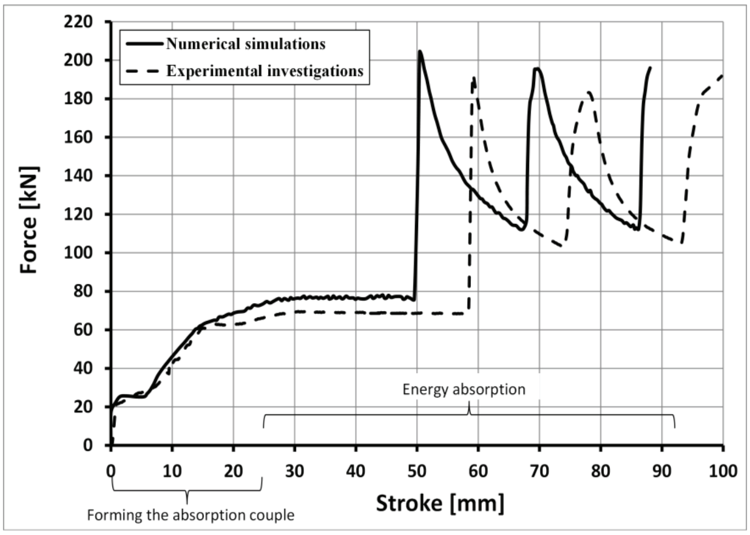

Fig. 13 Force vs. stroke diagram – numerical and experimental curves

Characteristic parameters which can be used for evaluation of this type of absorber are shown in the Table 1.

Table 1 Characteristic parameters

	F_{Imax} [kN]	F_{IImax} [kN]	H [mm]	W [kJ]	W_{sh} [kJ]
Numerical	76	204	62	7,3	4,6
Experimental (V = 0.17 mm/s)	66	172	68	7,3	4,5
Experimental (V = 25 mm/s)	69	191	68	8	4,6

The aim of this analysis was to compare two types of energy absorption elements and since it was performed using scaled model, as expected, scaled values of force and absorbed energy were obtained. Value of the amount of absorbed energy in case of implementation of shrinking tube process is given only in the last column of table 2. With the combined absorber, amount of absorbed energy is approximately twice as higher compared to tube shrinking absorbers, at the same stroke. This means that for the same amount of absorbed energy, tube absorber that works on principle of shrinking should have significantly larger dimensions which are not acceptable for the intended purpose. On the other hand, implementation of the combined method leads to gradual increase of force value, which can be noticed in the diagram and on the basis of characteristic values given in table 2.

5. Conclusion

Intensive work in the field of passive safety of railway vehicles is of great importance for Serbian railways, because great majority of its rolling stock doesn't have passive safety systems. According to the new international regulation, manufacturers of railway vehicles will be obliged to include elements of passive safety in the standard wagon equipment.

Using combined principle of energy absorption, absorption element with compact dimensions can be designed. Compact dimensions of combined absorbers allow using them on wagons and electric motor trains and also during refurbishment of existing passenger and freight wagons. This type of absorber may absorb significantly higher amount of collision energy in comparison with using only shrinking or folding process. Good correlation between results of numerical and experimental investigations indicates the possibility of using the developed numerical model for future research in this field. Good correlation may also decrease costs of development (dimensioning) of absorbers for different types of railway vehicles. On the other hand, experimental test of prototype of absorber cannot be excluded for final evaluation of the characteristics. Further steps will be experimental investigations on the full size combined absorber during collision of two passenger coaches.

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EKSPERIMENTALNA I NUMERIČKA ANALIZA KARAKTERISTIKA KOMBINOVANIH APSORBERA ENERGIJE SUDARA

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Predmet ovog rada su eksperimentalna istraživanja i numeričke simulacije kombinovanih apsorbera kinetičke energije sudara. Ovi elementi su deo pasivnih mera zaštite šinskih vozila. Ovaj tip apsorbera radi na principu kontrolisane deformacije koristeći proces sužavanja i gužvanja cevi. Ideja da se koriste ova dva procesa u paralelnom modu imala je za cilj da se, putem kontrolisanih deformacija uz ograničene dimenzije apsorbera, apsorbuje što je moguće veća količina kinetičke energije sudara. Apsorpcija energije se ostvaruje putem elasto-plastičnih deformacija cevi i trenjem između cevi i konusne čaure. Korišćenjem kombinovanog metoda, tokom sudara, apsorpcija energije počinje u cevi koja se sužava provlačenjem kroz konusnu čauru. Simultani proces gužvanja spoljne cevi počinje posle definisanog hoda, pa se obe cevi deformišu na preostalom hodu u paralelnom modu. Na ovaj način sila postepeno raste bez nepoželjnih pikova tokom čitavog hoda, što rezultira znatno većom količinom apsorbovane energije. Eksperimentalna istraživanja kombinovanog apsorbera realizovana su u laboratorijskim uslovima. Tokom eksperimentalnih istraživanja mereni su sila i hod. Numeričke simulacije su korišćene za proveru apsorpcione moći apsorpcionih elemenata pre eksperimentalnih istraživanja. Po završetku numeričkih simulacija i kvazi-statičkih testova, snimljeni podaci su analizirani i formirani su dijagrami sile u funkciji od hoda. Rezultati proračuna korišćenjem metode konačnih elemenata i rezultati eksperimentalnih istraživanja su u dobroj korelaciji.

Ključne reči: *eksperimentalna istraživanja, kombinovani apsorber, železnička vozila, pasivna bezbednost*