# Experimental and Numerical Determination of Tube Collision Energy Absorbers Characteristics

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*Development of collision energy absorbers is one of the necessary measures for passive safety of passenger coaches. The purpose of passive safety is to minimize the collision consequences for passengers. The collision absorber developed in this work consisted of a low carbon seamless steel tube and conical bush fabricated from quench and tempered carbon steel. During collision, the seamless tube is compressed into a bush with a reduced diameter. In this paper, the analysis of results is obtained by numerical simulations and dynamic investigation of tube absorbers of kinetic collision energy of passenger coaches. The research focuses on correlations between numerical and dynamic test results. Using the characteristic parameters obtained by the dynamic tests and numerical simulations, values for key numerical parameters have been defined, which can be used for further investigations of tube shrinking absorber. Numerical simulations should be used in the developing phase of a prototype, while for the final verification it is necessary to do dynamic (impact) test.*

**Keywords:** *energy absorber, passive safety, passenger coach, dynamic test, numerical simulations.*

## 1. INTRODUCTION

The subject of this paper is the development of a numerical model and dynamic investigations of modified collision energy absorber of passenger coaches [1]. The mentioned elements are parts of passive protection measures of railway vehicles. The development of elements for absorption of collision energy of railway vehicle represents an important segment in the design of new and reconstruction of the operating passenger coaches. The modified tube absorber is installed in a row with a standard buffer (stroke 110 mm) for passenger coaches [2]. The interface between the absorber and the buffer was realized by the shearing rings, which is designed to break at exactly defined load. The absorber works on the principle of compressing the tube into a ring using special bush with cone end. The absorber's role is to absorb as much of the collision kinetic energy as possible by controlled deformation, in order to protect the structure behind the absorption elements from deformation to the highest degree possible and thus protect the passengers. Energy absorption occurs by: *elastic-plastic deformation of the tube and friction between the ring and the tube*. Using the finite elements method, the nonlinear numerical simulation was realized. The numerical simulations were used to check the absorption power of absorption elements before the quasi-static and dynamic test. These simulations were focused on quasi-static and dynamic calculations. For quasi-static calculations, the key parameters were used defined in the paper [3,4]. Dynamic calculations were realized for different values of key parameters. The results given during dynamic simulations were used to define the key parameters for the next investigations of this type of elements. The experimental research focuses on quasi-static and dynamic tests. During the investigations the following values were measured: stroke, force, acceleration and velocity.

After the tests were completed, the recorded data were analyzed and force versus stroke diagrams of numerical simulation and dynamic test were made. At the end of this paper, the analysis of results and recommendations for the next investigations are given.

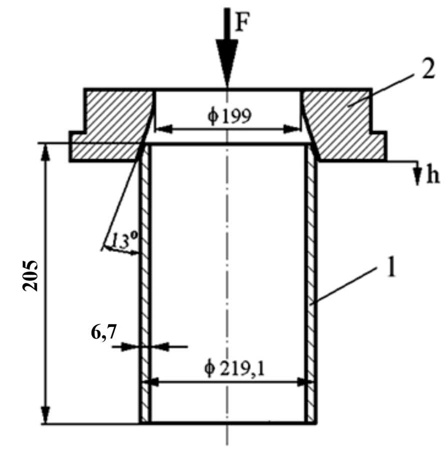


**Figure 1. Principle of the functioning of tube absorber**

## 2. NUMERICAL SIMULATIONS

According to the principle of work of collision absorber, a numerical model was formed using the following

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elements: seamless tube (pos. 1) from low carbon steel (material P235T1 steel) with dimensions Ø219.1 × 205 × 6.7 mm and the cone bush (pos. 2) from quenched and tempered carbon steel (material C45E) with dimensions Ø220/199 × 13º, Fig. 1 [1].

Using the finite elements method, the nonlinear numerical simulation on the plane axisymmetric elements (Fig. 2), on *Perzyna* model with rate dependent options was realized [1].

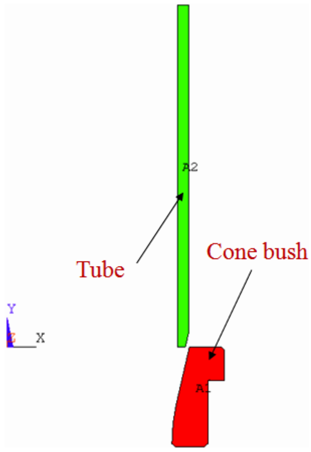


**Figure 2. Plane axisymmetric model**

Rate-dependent plasticity describes the flow rule of materials, which depends on time. The deformation of materials is now 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 rate, such as impact. *Perzyna* model has the following form [3,5]:

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

where: $\sigma$ is material yield stress, $\dot{\varepsilon}_{\mathrm{pl}}$ is equivalent plastic strain rate, $m$ is strain rate hardening parameter, $\gamma$ is material viscosity parameter, and $\sigma_0$ is static yield stress of material.

The key parameters which define a rate-depending option for this type of analyses are $m$ and $\gamma$.

Note that $\sigma_0$ is a function of some hardening parameters in general. As $\gamma$ tends to $\infty$, or m tends to zero or $\dot{\varepsilon}_{\mathrm{pl}}$ tends to zero, the solution converges to the static (rate-independent) solution.

Numerical simulations were realized using the *PLANE 42* element. This element is used for 2D modeling of solid structures. The 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 nonrecoverable strain, begins when stresses exceed the material's *yield point*. In accordance with previous for these calculations *bilinear characteristic of material* is used. The *Bilinear Isotropic Hardening* option uses the *von Mises yield criteria* coupled with an isotropic work hardening assumption. This option is often preferred for large strain analyses.

When modeling the $\sigma$ ($\varepsilon$) curve, which is used in the calculations, the initial slope of the curve was taken as the modulus of elasticity – $E$. Since the yield stress curve continues to limit slope defined by tangent module – $E_{\mathrm{tang}}$ expressed in the same units as the modulus of elasticity, Fig. 3 [1,5]. The value of tangential modules cannot be less than zero or greater than the value of the modulus of elasticity. For P235T1 steel values of characteristic parameters are: $E$ = 2.1 E11 N/m$^2$ and $E_{\mathrm{tang}}$ = 1.45 E9 N/m$^2$ [5].

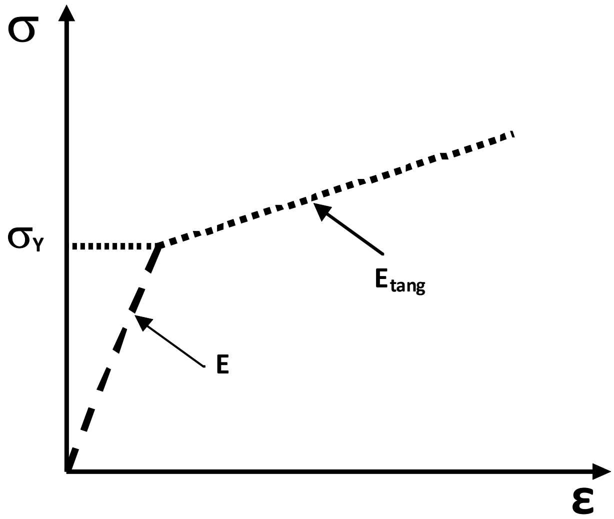


**Figure 3. Bilinear characteristic of material**

Having in mind the 2D models included in these calculations, the contact *surface to the surface* element is used.

Two numerical simulations were done: quasi-static and dynamic. For quasi-static simulations, the values for key parameters are as follows: $m$ = 0.403 and $\gamma$ = 305 [3].

Dynamic numerical simulations included different values of parameters $\gamma$ with constant values of the parameter $m$ and vice versa.

## 3. EXPERIMENTAL INVESTIGATIONS

Investigations of impact absorption used the following methods: quasi-static pressure loading (hydraulic press) and dynamic-impact load (collision of two passenger coaches). Taking into account the required dimensions of the buffer [2] and frontal part of the supporting vehicle structure, required amount of absorbed energy [6] and previous experience [7], the research was performed on the following elements: seamless tube-1 from low carbon steel (P235T1) and the bush with cone end-2 from quenched and tempered carbon steel

(C45E), Fig. 4. Other position in Figure 4 shows the elements of the assembly of the absorber.


**Figure 4. Elements of tube shrinking absorber type samples**

Measurement of the compression stroke was realized via potentiometer movement transducers and measurement of the compression force was performed using a special transducer constructed on the base of measuring tapes connected into a full bridge. Acceleration and velocity was measured via special transducer for this assignment.

### 3.1 Quasi-static test

Quasi-static tests were performed on a Litostroj hydraulic press with a maximal force of 2500 kN. During the experiment, the impact stroke *h* and compression force *F* were measured. Measurement of the compression stroke was realized via two potentiometer movement transducers of the PM2S 150 type (Table 1) that were installed in parallel. With the purpose of eliminating possible slanting of supporting surfaces, the average value of movement of two transducers is taken as valid.

**Table 1. Basic characteristics of the of the movement transducer**

| Transducers | DT1, DT2 |
|---|---|
| Producer | ELAP Spa, Italy |
| Type | Potentiometer transducer with thin film |
| Type denotation | PM2S 150 |
| Stroke | 150 mm |
| Nominal resistance | $R_0 = 5$ kΩ |
| Allowed current | 18 mA |
| Life | $20 \cdot 10^6$ cycles |
| Linearity | 0.075 % FS |
| Insulation resistance | 1000 MΩ |
| Movement force | 1.0 N |
| Operating temperature | – 10 ºC ... + 65 ºC |

Measurement of the compression force was done using a special transducer (Table 2) constructed on the base of measuring tapes connected into a full bridge, where temperature self-compensation was accomplished. Tape positioning provided no sensitivity to the eccentric force action.

Acquisition and analysis of data were performed using the *Spider 8* (Table 3) measurement acquisition system. All measurements were followed and recorded using the *Catman 32 Express* software package.

**Table 2. Basic characteristics of the force transducer**

| Transducer | Unit | FT2 |
|---|---|---|
| Nominal measuring range | kN | 1500 |
| Sensitivity | mV/V/1 MN | 0.881 |
| Deviation from linear + hysteresis | % FS | < 1.3 |
| Reference temperature | ºC | 20 |
| Mass | kg | 30 |

**Table 3. Basic characteristics of the „Spider 8“ system**

| Producer | Hottinger Baldwin Messtechnik | |
|---|---|---|
| Model | Spider 8 / SR55 | |
| Accuracy class | | 0.1 |
| Measurement buffer | Mer | < 20,000 |
| Sampling rate (21 levels) per channel | 1/s | 1 ... 9600 |
| Carrying frequency (sinus / symmetrical) | Hz | 4800 |
| Impactor cable length | m | 50 |
| Nonlinearity in relation to the nominal value | % | 0.05 |
| Operating temperature range | ºC | – 20 ... + 60 |
| Power | W | 4 / 0.25 |
| Dimensions ($l \times h \times w$) | mm | 330 × 75 × 270 |
| Mass | kg | 2.75 / 0.05 |

Quasi-static test is used for performing the absorption couples. During this test, two tubes were compressed approximately 70 mm in the cone bushing. In this pre-deformed form the absorption elements should be mounted on the front of the railway car structure. Two absorbers were mounted on the end of the wagon with the following signs: S1-P8 and S2-P9, Fig. 5.


**Figure 5. Assembly of absorber**

### 3.2 Dynamic-impact test

Dynamic tests were realized via the collision of two passenger coaches on the open railway track in GOSA Rolling Stock Company. The collided passenger coach, equipped with absorbers (coach No 2, Fig. 6), was standing on the railway, while the colliding coach (coach No 1, Fig. 6) was equipped with standard buffers and force transducers.

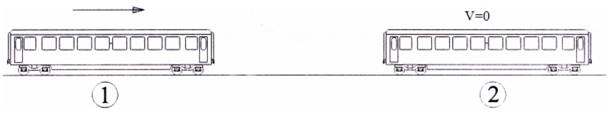


**Figure 6. The scenario of a collision**

During testing the following parameters were measured: force, stroke (buffer stroke and tube absorber stroke), speed and acceleration. The characteristics of force transducers are given in Table 2. In order to measure the buffer and absorber strokes, the SLS 190 potentiometer movement transducers, intended for higher speeds of deformation (details are given in Table 4), were used.

**Table 4. Basic characteristics of the movement transducer SLS 190**

| | |
|---|---|
| Transducer | SLS 190 |
| Producer | Penny + Gilles, UK |
| Type | Potentiometer transducer with thin film |
| Type denotation | SLS 150 |
| Stroke | 275 mm |
| Nominal resistance | $R_0 = 11$ kΩ |
| Life | $20 \cdot 10^6$ cycles |
| Linearity | 0.05 % |
| Insulation resistance | 100 MΩ |
| Max velocity | 10 m/s |
| Operating temperature | – 30 °C ... + 100 °C |

Data acquisition and analysis of results were performed using two “Spider 8” acquisition systems (Table 3) connected to two laptop computers with the installed “Catman 32 Express” software package.

During testing two collisions were performed: the first at the speed of 11.4 km/h and second at 19.7 km/h, Fig. 7. The Diesel engine – a shunting locomotive – was used for a running start of the coaches. The speed of a running start was controlled by the GPS device.

## 4. RESULTS

### 4.1 Numerical results

After the quasi-static and dynamic simulations were completed, the given results were analyzed and force versus stroke diagrams were formed.

Figure 8 shows force versus stroke diagram obtained by quasi-static numerical simulations. The values of key calculation parameters $m = 0.403$ and $\gamma = 305$ were used [3]. The maximum value of force reached at this phase is ≈ 700 kN, while the value of force on the stroke ≈ 70 mm is ≈ 600 kN.

**Figure 7. Dynamic-impact test**

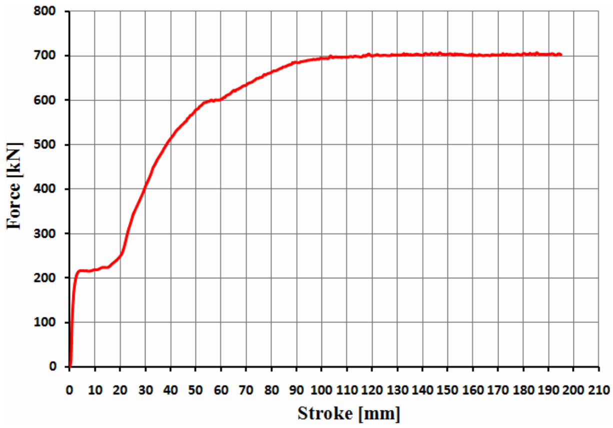


**Figure 8. Force versus stroke diagram – quasi-static numerical simulations**

Figure 9 shows force versus stroke diagram obtained by dynamic numerical simulations realized for different values of parameter $\gamma$ ($g = \gamma$) and constant values for parameter $m$ [8,9]. This diagram shows that the lower values of parameter $\gamma$ give higher values of the force and vice versa.

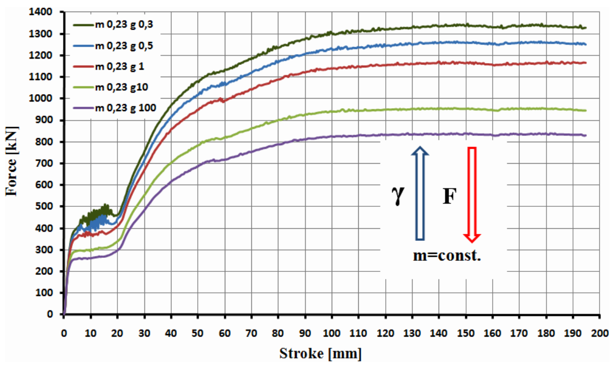


**Figure 9. Force versus stroke diagram – dynamic numerical simulations for *m* = const.**

This means that increase of strain rate gives increase to the values of force and vice versa.

In the other case, Figure 10 shows that different values of parameter $m$ with constant values of parameter $\gamma$ do not give significant deviation of force values.

### 4.2 Experimental results

After the quasi-static and dynamic tests were completed, the recorded data were analyzed and force versus stroke diagrams were made.

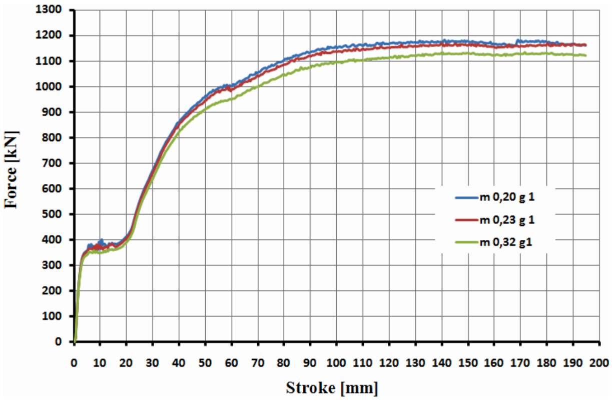


**Figure 10. Force versus stroke diagram – dynamic numerical simulations for $\gamma$ = const.**

Figures 11 and 12 show force versus stroke diagrams obtained by the quasi-static test.

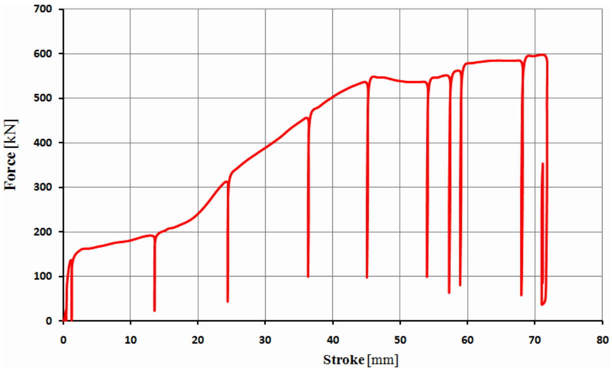


**Figure 11. Force versus stroke diagram – absorption couple S1-P8 – quasi-static test**

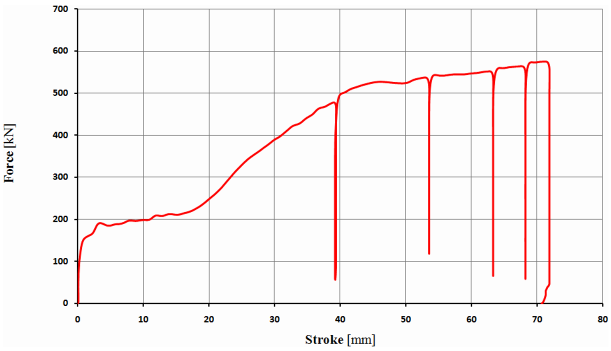


**Figure 12. Force versus stroke diagram – absorption couple S2-P9 – quasi-static test**

Both diagrams show similar flow of forces. The force increases uniformly on the whole stroke. Maximal values of force (for both absorption couples) are ≈ 600 kN on the stroke of ≈ 70 mm.

Typical dependence of the compression force on the stroke function obtained from dynamic investigations with impact velocity of 11.4 km/h is presented in Figures 13 and 14.

In the S1-P8 (Fig. 13) diagram two phases can be clearly separated. In *the first phase* the absorber works until the stroke ≈ 106 mm. Then, the blockage of buffer springs occurs and fracture of the shearing ring (intermediate phase), which is also indicated by a rapid drop of the force after it has reached the value of ≈ 705 kN. At the end of the energy absorption process, the maximum force value is ≈ 1050 kN. The force flow of the S2-P9 (Fig. 13) absorption couple is identical as for the S1-P8 couple. In this case, the shearing ring fracture occurred at the force value of 816 kN with a stroke of ≈ 97 mm. Maximum force value reached in the third phase was up to ≈ 800 kN.

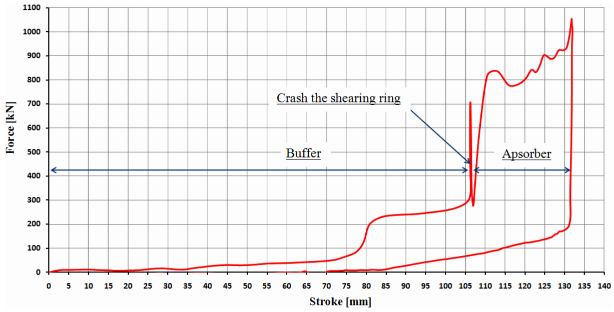


**Figure 13. Force versus stroke diagram – absorption couple S1-P8 – *V* = 11.4 km/h**

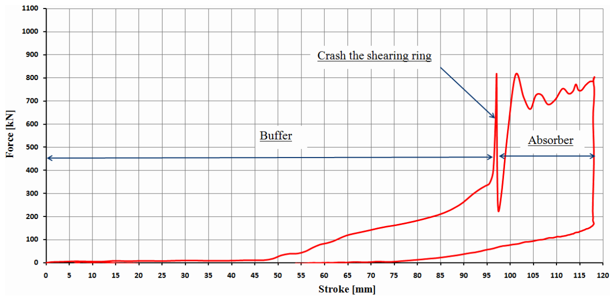


**Figure 14. Force versus stroke diagram – absorption couple S2-P9 – *V* = 11.4 km/h**

Figures 15 and 16 show the dependence of the compression force on the stroke function obtained from the second impact at the velocity of 19.7 km/h.

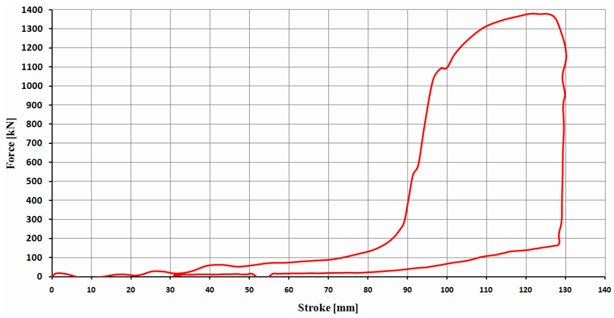


**Figure 15. Force versus stroke diagram – absorption couple S1-P8 – *V* = 19.7 km/h**

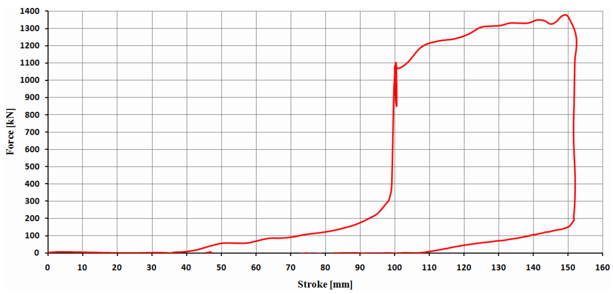


**Figure 16. Force versus stroke diagram – absorption couple S2-P9 – *V* = 19.7 km/h**

As the fracture of shearing ring occurred during first collision, there is no intermediate phase in the presented diagrams, only *the first* (*buffer*) and *second phase* (*absorber*) of absorption energy. This is noticeable in the diagrams in the transition from the first phase to the second with a stroke of ≈ 100 mm. Maximum force values obtained during the second collision are: 1380 kN on the S1-P8 first absorption couple and 1375 kN on the S2-P9 absorption couple.

Table 5 contains the parameters of significance for evaluating elements for energy absorption of the collision of passenger coaches obtained by quasi-static and dynamic investigations.

**Table 5. Characteristic parameters**

| | Absorption couple | $V$ [km/h] | $F_{max}$ [kN] | $F_{av}$ [kN] |
|---|---|---|---|---|
| Quasi-static test | S1-P8 | – | 596 | – |
| | S2-P9 | – | 575 | – |
| Dynamic test – I | S1-P8 | 11.4 | 1053.30 | 895.65 |
| | S2-P9 | 11.4 | 816.6 | 746.87 |
| Dynamic test – II | S1-P8 | 19.7 | 1380 | 1269.42 |
| | S2-P9 | 19.7 | 1375 | 1241.97 |

## 5. CONCLUSION

Based on the characteristic parameters obtained during dynamic tests and dynamic numerical simulations, values for key parameters of the material model have been defined, $m$ = 0.23 and $\gamma$ = 0.3. These parameters may serve for the next investigations of tube shrinking absorber for the impact velocity of more than 20 km/h. Quasi-static test confirmed that the values of the key parameters $m$ = 0.403 and $\gamma$ = 305 are appropriate for this type of calculations and can be used for the next investigations. Numerical simulations should play a key role in the development phase of a prototype design, while for the final verification it is necessary to perform dynamic (impact) test.


## ACKNOWLEDGMENT

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## ЕКСПЕРИМЕНТАЛНО И НУМЕРИЧКО ОДРЕЂИВАЊЕ КАРАТЕРИСТИКА ЦЕВНИХ АПСОРБЕРА КИНЕТИЧКЕ ЕНЕРГИЈЕ СУДАРА


**Јован Д. Танасковић, Драган Д. Милковић, Војкан Ј. Лучанин, Горан Ж. Симић**



Развој апсорбера енергије судара је једна од неопходних мера пасивне заштите путничких вагона. Улога пасивне заштите је да последице судара сведе на најмању могућу меру. Апсорбер развијан у овом раду састоји се од челичних бешавних цеви у квалитету P235T1 и конусне чауре направљене од челика за побољшање у квалитету C45E. Током судара провлачењем цеви кроз конусну чауру долази до редукције – смањења пречника цеви при чему се троши енергија. У раду су анализирани резултати добијени нумеричким симулацијама и динамичким испитивањима цевних апсорбера кинетичке енергије судара путничких вагона. Главни циљ рада је успостављање корелације резултата добијених нумеричким симулацијама и експерименталним истраживањима. Коришћењем карактеристичних параметара добијених током квази-статичких, динамичких испитивања и нумеричких симулација, дефинисане су вредности кључних параметара које се могу користити за будућа испитивања цевних апсорбера овог типа при брзинама већим од 20 km/h. Нумеричке симулације се могу користити у фази развоја апсорпционих елемената док је за коначну оцену прототипа неопходно урадити динамичка испитивања.