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SPECIAL SECTION

Adaptive crash energy absorber based on a granular jamming mechanism

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Abstract. The following discussion concerns the use of innovative smart materials called vacuum-packed particles (VPPs) as active energy absorbers. VPP, also known as a granular jamming system, is a structure composed of granular media contained within an elastomer coating. By changing the vacuum pressure inside the coating, it is possible to control the mechanical properties of the structure. VPPs have many applications, e.g. in medicine, robotics, and vibration damping. No attempts have yet been made to use VPPs to absorb the energy of a collision, although, given their properties, this could very well be an interesting application. In the first part of the paper, the general concept of the absorber is presented. Then a prototype and the empirical tests conducted are precisely described. The middle part of the paper considers the basic properties of VPP and modeling methodology. A proposal for a constitutive equation is presented, and a numerical simulation using LS-Dyna was performed. In the final section, the concept of a smart parking post is presented.

Key words: granular jamming; smart structures; crash energy absorption.

1. INTRODUCTION

Collisions between bodies are very common in the real technical world [1]. In order to minimize the loads arising during such impacts [2], energy dissipators are used. Typically, an absorber uses special passive components designed to minimize the effects of the most likely events. In real mechanical systems, it is desirable to be able to change the parameters of the dynamic response of the system depending on the collision conditions, which is why solutions allowing for active control of the response characteristics are increasingly used. Collision energy dissipators are used in many industries, including automotive [3], railway [4], or aviation [5]. Numerous technical solutions have been developed to help reduce the effects of collisions. One of the most popular solutions is the crumple zone in a car, which allows energy to be absorbed during a collision. From the very beginning of aviation, objects were equipped with energy dissipators for reducing the load during a collision with the ground during landing, In the literature, you can find an absorber for reducing the load during the process of automatic parcel delivery by a flying object [5], or an airbag for preventing damage to the multirotor during a collision with the ground [6]. There are many collision energy absorber solutions in onshore infrastructure such as road barriers [7] Almost all the absorbers mentioned above are passive solutions. One reason for this is the complexity of these structures, and the price and the weight of devices that make the adaptive absorption of mechanical energy possible [8]. Therefore, it seems reasonable to look for new solutions enabling meeting this requirement. An analysis of the mechanisms of collision energy dissipation and the disadvantages of commonly available active absorbers suggests that an energy absorber based on the mechanism of granular jamming [9–11], where it is possible to control the dissipation properties by means of the vacuum parameter, could prove effective in dissipating impact energy. Materials based on granular jamming are usually called vacuum-packed particles (VPPs). They consist of particles made of polymers, metals, or others [12], surrounded by elastomer coating. By changing the vacuum pressure inside the envelope, it is possible to regulate the stiffness characteristic. Some examples of VPP granulates and a beam made of such materials are shown in Figs. 1 and 2.

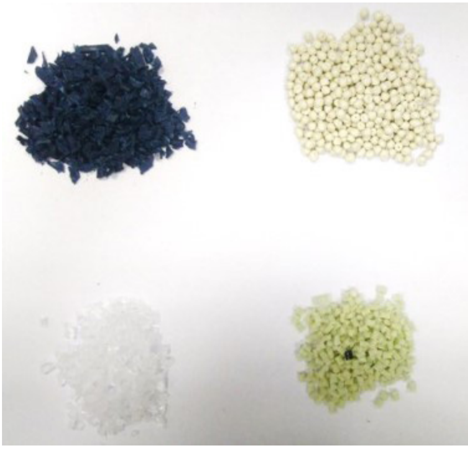

Fig. 1. An example of particles used in VPP (PC+ABS C1200HF, POM, ABS)

Such structures have been used commercially in different areas of industry. In paper [13] the authors show an example of using VPPs in a vacuum mattress and work [14] as an endoscope. Some attempts have been made towards using VPPs as

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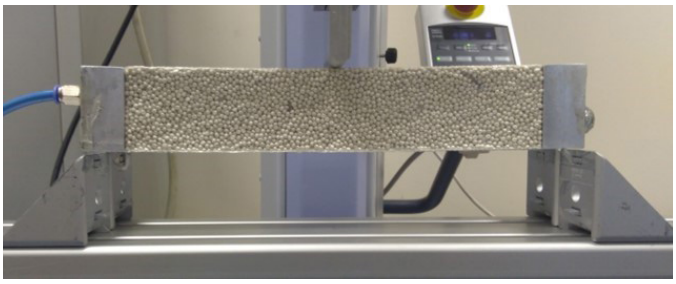

Fig. 2. A beam made of VPPs

an orthesis [15]. At present, they are becoming increasingly popular in the area of soft robotics for example as a universal gripper [16, 17] that can handle objects having different shapes. In the field of mechanical engineering, the most popular application is the vibration damper [18, 19]. The mechanical properties of VPPs have been tested for many years. Paper [20] shows the influence of vacuum pressure on the material behavior, whereas work shows the influence of grain type [12, 21]. The effect of the outer shell on the mechanical properties has also been tested [22].

Generally, it can be said that the empirical and numerical tests of VPPs presented in literature have demonstrated an interesting feature of VPPs in terms of using them as active dissipators of collision energy. The material deforms like a visco-plastic solid when the negative pressure inside the material is greater than 0.03 MPa. After deformation, the granulate can be reorganized by reducing the internal negative pressure to a value close to zero or by introducing a positive pressure. In this way, it is possible to ensure that the absorber returns to its original equilibrium position by means of small spring forces. This innovative mechanism enables such a dissipater to be used multiple times, something that is virtually impossible in the case of classic devices that dissipate energy through plastic deformation.

And so, the concept of an energy absorber that allows the active dissipation of impact energy – regardless of the direction of impact – is an original contribution to the current state of the art. Such a device could be used, for example, as an adaptive parking bollard.

2. GENERAL CONCEPT OF THE ABSORBER – DESIGN AND TESTS

A block diagram of the proposed solution is presented in Fig. 3. Figure 4 shows the structural concept of the absorber.

Fig. 3. Block diagram

The dissipator is equipped with sensors that monitor its surroundings and provide information to the control computer regarding the position and speed of the impactor. On that basis, the optimal energy dissipation strategy is calculated, and then the dispersing elements are adapted; in this solution, that role is played by the granular jamming mechanism. After the collision, the negative pressure is reduced to zero (or excess pressure is introduced) and, with the assistance of additional elastic elements, the absorber can return to its equilibrium position.

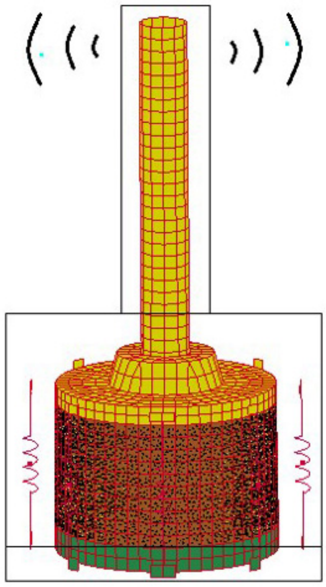

Fig. 4. Preliminary absorber concept

The great advantages of VPPs are that their characteristics can be controlled and that they can be reused multiple times. The assumed characteristics of an absorber are shown schematically in Fig. 5.

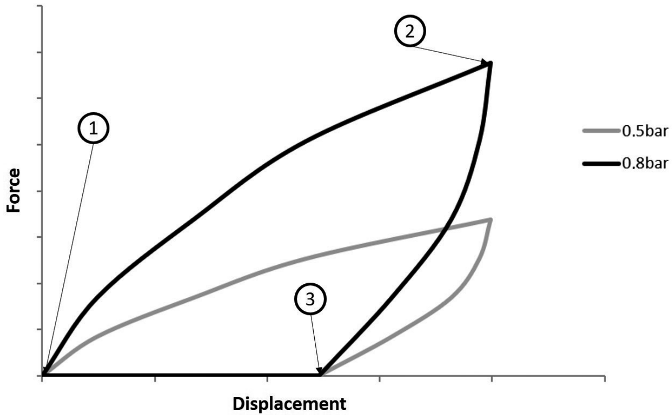

Fig. 5. Conceptual absorber characteristic

The curve from 1–2 illustrates the dissipator loading process, while the curve from 2–3 shows its behavior during unloading. At point 3, the absorber is no longer loaded with external force. Since it has been plastically deformed, the absorber does not return to the equilibrium position after unloading. When the vacuum value is reduced to zero (atmospheric pressure), the interaction forces between the granulate are relatively small, and so, with an appropriate selection of the elastic element that transfers the moments parallel to the granulate, the absorber can return to equilibrium (the curve from 3–1). Thanks to this unique property, it is possible to use the absorber many times, which is a great advantage. Figure 5 shows two sample characteristics for different values ??of the negative pressure inside the core. The differences in their shapes illustrate the possibility of regulating the dissipative properties in the case of impulse excitations.

3. ABSORBER CONSTRUCTION AND TESTING

To check the basic functionality of the proposed concept, a prototype was built. The absorber structure is presented in Figs. 6 and 7.

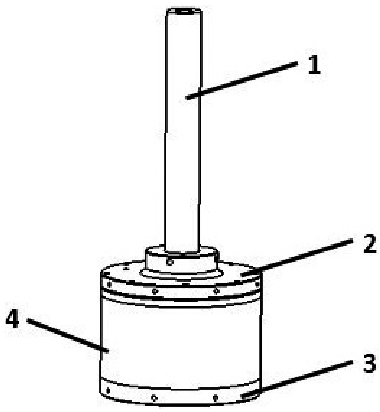

Fig. 6. Basic absorber view

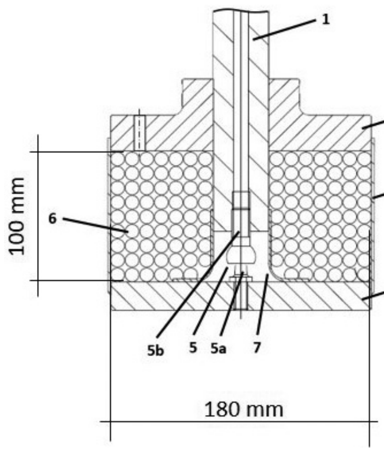

Fig. 7. Detailed absorber view

The device is built with two plates (2, 3) connected by a jointed bar (1). The space between the plates is filled with granular matter (6) and surrounded by an elastomer coating (4). Because the interaction forces between the granules of the core material can be changed by changing the negative pressure, it is possible to adjust the bending stiffness of the absorber, thus shaping the system response to the force of an impact. Additionally, the absorber is equipped with the spring which allows restoring the equilibrium state after the loading (previously vacuum need to be switched off). The absorber was filled with a packing fraction of 57%, with granular particles having a diameter of about 3 mm made of plastic POM MT24u01 with a Young modulus of 2900MPa. The outer shell was made of polyethylene with a thickness of 0.15 mm and a Young modulus of 10 MPa. Before each test, the absorber was placed in a special mold which facilitates keeping the proper and repeatable shape. After that, the partial vacuum was applied and the mold was removed. The sample prepared in such a way was ready to be tested. Especially, the response of the device to higher velocities was investigated. The procedure was similar to other research of VPPs presented in papers [12, 20]. Dynamic tests were conducted using an MTS actuator mounted on a dedicated test stand, as illustrated in Fig. 8. The distance between base and actuator was equal to 300 mm. Tests were carried out for five different vacuum values (0.01 MPa; 0.03 MPa; 0.05 MPa; 0.07 MPa; 0.09 MPa) and three deformation velocity values (50 mm·s^{-1}; 300 mm·s^{-1}; 450 mm·s^{-1}). Each test was repeated 3 times.

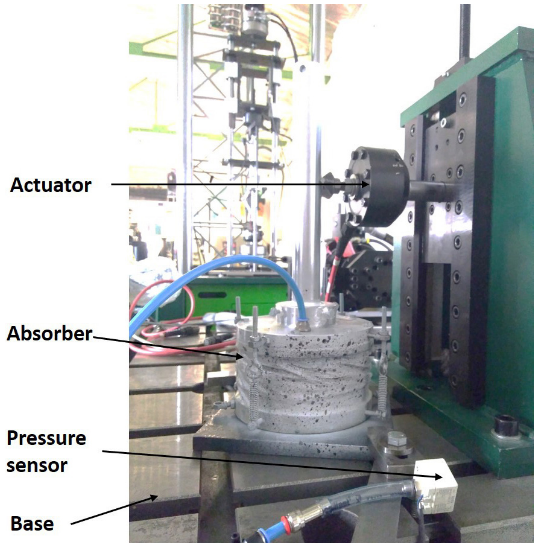

Fig. 8. Test stand

During the load, a kinematic excitation with a triangular shape and a displacement value of 10 mm was applied, and the values of force as a function of displacement were recorded.

Figure 9 shows the force-displacement curves for a different value of underpressure and velocity equal to 50 mm·s^{-1}. It was shown that the maximum force was changed from 120 N for the lowest value of underpressure to 500 N for the highest, which is a change of over 400%. Additionally, Fig. 10 shows the influence of loading velocity on the absorber behavior at an underpressure of 0.09 MPa. This research shows that the influence of the velocity is not significant (is only about 5%).

In a crash energy absorber, the energy dissipation characteristic is crucial; it is calculated according to Equation (1):

$$E = \int_0^{\delta_{\max}} P(\delta)\,\mathrm{d}\delta , \tag{1}$$

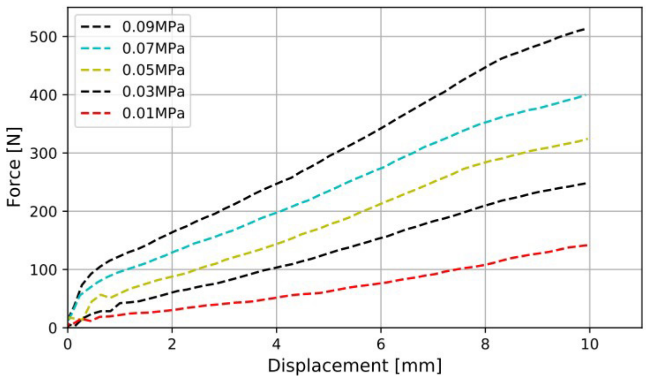

Fig. 9. Force-displacement curves

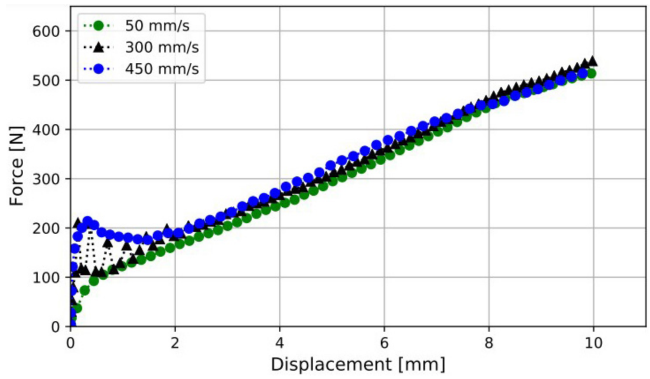

Fig. 10. Force – displacement under different velocities and partial vacuum value 0.09 MPa

where $P(\delta)$ is the instantaneous crushing force of a given member, δ and δ_{max} are, respectively, the current and maximum attainable crush distances. Figure 11 shows the energy as a function of displacement for 5 different values of vacuum pressure. It can be seen that the absorption capacity increases with increasing negative pressure. This can change within a range from 1.25 J to 3 J.

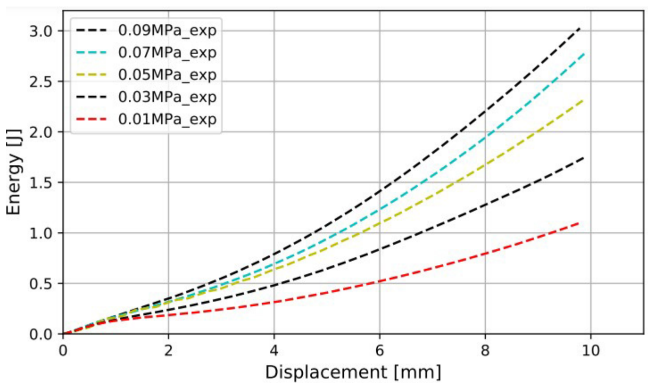

Fig. 11. Energy – displacement curve

The empirical tests performed on this pre-prototype showed that it is possible to change the dissipation characteristic by means of the external vacuum signal. These results are interesting and show that it is worth continuing the research and development work. To build a real engineering object, however, a long development process supported by simulations will be necessary.

4. VPP MODELING

Because of their properties, VPPs are difficult to model. The main problem is their asymmetric yield characteristic. Such materials have different properties for tension and compression, as is illustrated in Fig. 12, which shows yield stress as a function of vacuum pressure for both tension and compression. Additionally, our material displayed some strain rate hardening, which must be considered when modelling a device such as a crash energy absorber.

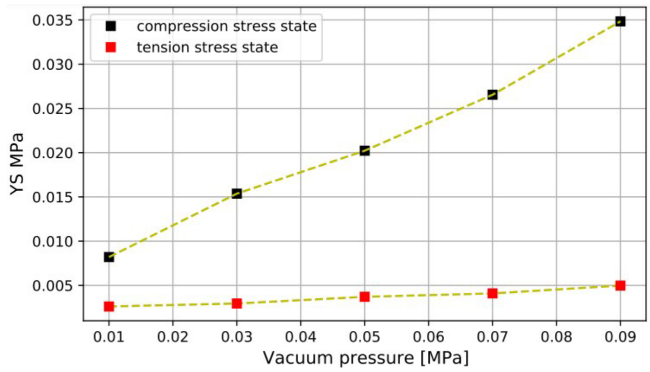

Fig. 12. YS in the function of vacuum pressure

To take all the relevant properties into account, a plasticity model described by Equation (2) was proposed:

$$\begin{cases} \Phi = \frac{1}{2} s_{ij} s_{ij} - \frac{\sigma_{y+/-}(\varepsilon, \dot{\varepsilon}, T, p)^2}{3} \leq 0, \\ \sigma_{y+/-}(\varepsilon, \dot{\varepsilon}, T, p) = \begin{cases} \sigma_{y+}(\varepsilon, \dot{\varepsilon}, T, p) & \text{if } I_\sigma > 0, \\ \sigma_{y-}(\varepsilon, \dot{\varepsilon}, T, p) & \text{if } I_\sigma < 0, \end{cases} \end{cases} \tag{2}$$

where Φt is a plasticity function, s_{ij} deviatoric components of the stress tensor, $\sigma_{y+/-}(\varepsilon, \dot{\varepsilon}, T, p)$ radius of plasticity function.

Generally, this is an extension of HMH rules [23], but one that considers the fact that the plasticity radius is different for the tension and compression stress states. The radius is described by equation (3):

$$\sigma(\varepsilon, \dot{\varepsilon}, T, p) = \left(\alpha + \beta p + (\Psi + \gamma p)\varepsilon^{\Upsilon - \chi p}\right) \left(1 + (\Xi - \mu p)\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right), \tag{3}$$

where α, β, Ψ, γ, Υ, χ, Ξ, μ are a material constants. This is an extension of the Johnson–Cook [24] model that takes the effect of vacuum pressure into account. Since no change in temperature is considered in this work, the relevant part of the original equation was omitted. This model was implemented in a Ls-Dyna solver by an extension of the mat_124 model.

The material constants for VPPs made of POM listed in Table 1 were identified from the results from uniaxial tension and compression tests. The identification process was performed using the Lavenberg–Marquardt optimalization algorithm, as was precisely described in paper [24]. A comparison between the simulation and the experiments for uniaxial compression is shown in Fig. 13. The empirical results came from uniaxial tests performed on cylindrical samples. The engineering strain and stress were calculated based on force and displacement values recorded on a test stand. The samples had an initial length equal to 100 mm and a diameter of 51 mm.

Table 1
Material properties of the considered materials

α_-	β_-	Ψ_-	γ_-	Υ_-	χ_-	Ξ_-	μ_-
0.0095	0.6625	2.28	2.125	0.923	1.25	0.0896	0.33
α_+	β_+	Ψ_+	γ_+	Υ_+	χ_+	Ξ_+	μ_+
0.0019	0.0358	0.105	5.375	0.603	-1.81	0.0314	-0.55

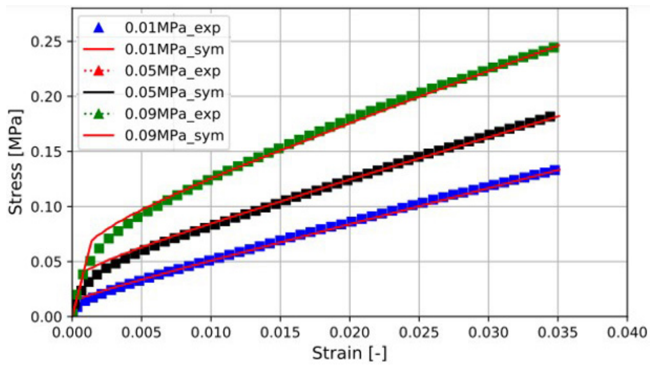

Fig. 13. Comparison between test and simulations

To check that the proposed method works correctly, a simulation of the crash absorber porotype was made, followed by a comparison between the tests and the simulations. First, an FE [25] model, illustrated in Fig. 14, was built in LS-PrePost. The model dimensions are the same as the prototype illustrated in Figs. 7 and 8. Elements made of aluminum alloy, pipe, and two plates, were modeled using a linear elastic material model, with shell and solid elements, respectively, and with dimensions of 5 mm. The full integrated shell and solid element were chosen, 4-node and 8-node respectively. Spring was modeled with 1D elements with a linear characteristic. The main part of the absorber – the core made of VPPs – was modeled with 3D hexagonal elements with a nonlinear material model described by equations (2) and (3). The average size of these elements was 3 mm.

The boundary and initial conditions were applied analogues to tests. The bottom plate was constrained by 6 degrees of freedom. The loading elements were accelerated to a velocity of 460 mm·s^{-1}. Between the loading elements and the absorbers, a penalty contact was assumed. This is precisely illustrated in Fig. 15. Simulations were performed for four different values of

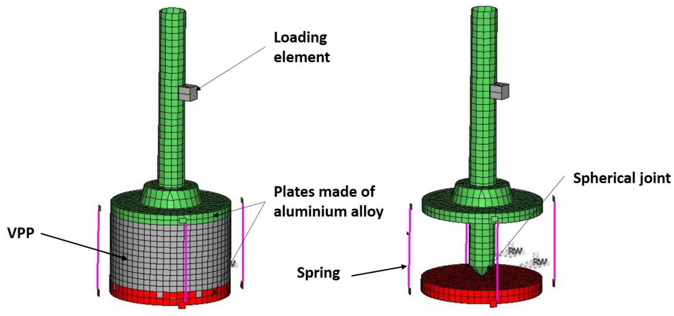

Fig. 14. FE model

vacuum pressure (0.03 MPa, 0.05 MPa, 0.07 MPa, 0.09 MPa). A vacuum pressure of 0.01 MPa was not considered in this analysis since the authors' previous works have shown that modeling approaches that treat VPPs as a continuum solid body do not work at vacuum pressures lower than 0.03 MPa. Due to the further considerations of the research, work concerns only vacuum pressures within a range of from 0.03–0.09 MPa.

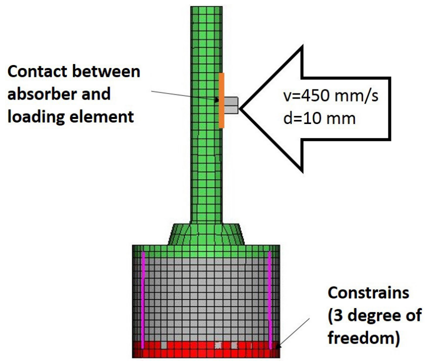

Fig. 15. Boundary and initial conditions

During all simulations, the dissipated energy, contact force, and displacement of the loading elements were measured. All the simulation results were compared with the test results presented in Section 3. Figure 16 shows dissipated energy as a function of displacement for four values of vacuum pressure. The simulation results are described by the continuous black

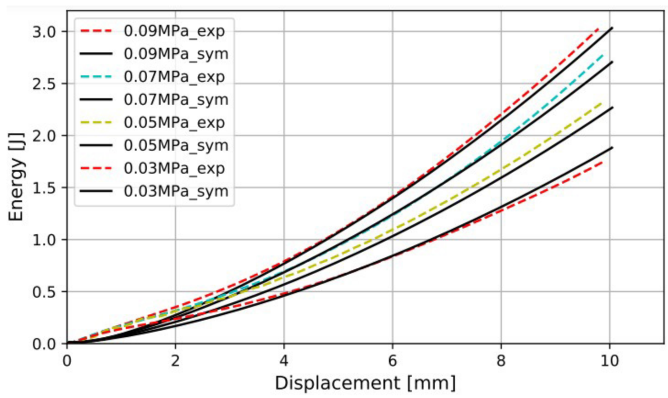

Fig. 16. Dissipated energy in the function of displacement – test vs simulations

line and the test results by the dashed line. It can be noticed that, generally, the correlation is very close for all the tests over the whole range of displacement, with the worst correlation in the range of 0–3 mm, after which it stabilizes and, for the highest value of displacement, is less than 5%.

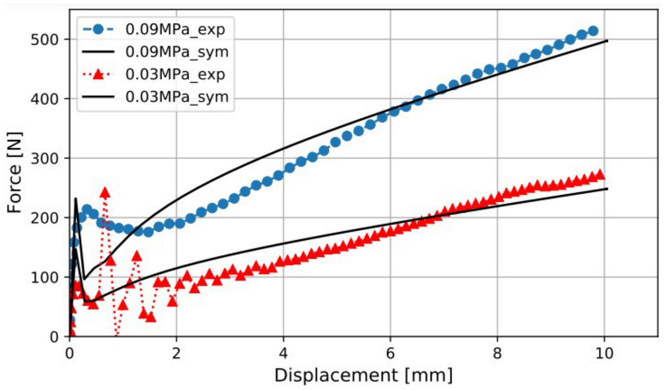

Fig. 17. Force in the function of displacement – test vs simulations

Figure 16 also shows force as a function of displacement, but to make the figure clearer, only two vacuum pressures, the lowest and highest, were compared. It can be seen that in this case the differences are the greatest also in the 0–3 mm range. This may be due to the simple contact model that was proposed. For higher values of displacement, the correlation is very close and the error, which was calculated according to formula (4), is lower than 5%.

$$\mathrm{ERROR} = \frac{F_{\mathrm{model}} - F_{\mathrm{test}}}{F_{\mathrm{test}}}\,. \tag{4}$$

In the process of designing an energy absorber, it is crucial to be able to predict its energy dissipation and maximum force, for these determine the critical loads of the protected object. Since the absorber has a hardening characteristic, the maximum force occurs for the highest value of displacement Therefore, it was concluded that the modeling methodology works correctly and can be used for further design work.

5. ADAPTIVE PARKING POST – POSSIBLE APPLICATION

An interesting application of a smart absorber based on the granular jamming mechanism could be a parking post that would change its stiffness depending on the impact conditions. The structure of the post must, first of all, transfer the basic operational loads resulting from the mass or surface loads. Additionally, the structure should be able to withstand certain abnormal loads due to misuse (e.g. deliberate hitting by a pedestrian). The need to bear these loads makes it necessary to ensure that the post is sufficiently stiff, which may be unfavorable in some situations. A typical example would be a collision with a car in the case where the vehicle driver did not notice the presence of the post. In such a situation, it would be advantageous to be able to suddenly reduce the stiffness of the absorber. The purpose of low stiffness would be to minimize the damage to the vehicle resulting from the collision. On the other hand, in the case where there was an object or person behind the post, the post could increase its stiffness to absorb a significant part of the energy and halt the vehicle.

Based on previous research, it was decided to modify the structure to make it more compact and allow for greater deformation. This was achieved by placing the spring element inside the absorber. Additionally, it was formed in an accordion shape that permitted greater deformation. The concept of the smart parking post is shown in Fig. 18.

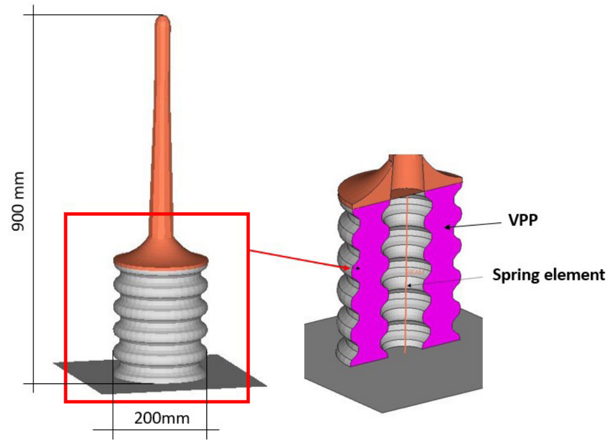

Fig. 18. The concept of smart parking post

To verify the concept, numerical simulations were made using an FE model of a Honda Accord prepared by the NHTSA (National Highway Traffic Safety Administration). This complex car FE model was validated based on the test results. The car model was integrated with the absorber, as shown in Fig. 19. The dimensions of the absorber are presented below but the modeling methodology, like the type and size of elements, and material model are analogous to those described in Section 4.

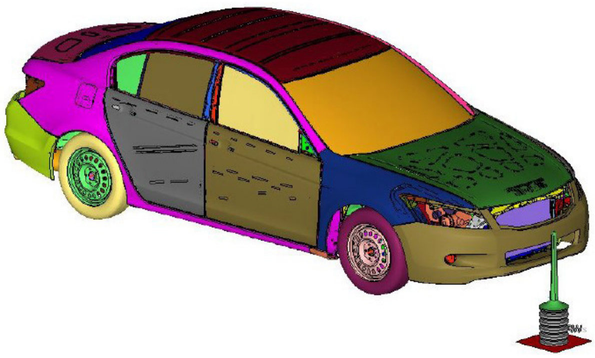

Fig. 19. Car and absorber – FE model

Two crash simulations were carried out, with the same initial conditions but different material characteristics of the VPP resulting from a change in the negative pressure parameter inside the granulate. The initial car velocity was equal to 55 km/hr. There was a contact between the ground and vehicle wheels and the gravitational acceleration of 9.81 m/s2. The base of the absorber was fully constrained and the contact between the car and absorber was added.

Using the proposed material model, it was possible to conduct simulation studies that took account of only one variable (the p parameter). Figure 20 shows the dissipated energy for two parking post configurations, a "rigid" (vacuum pressure 0.09 MPa) and a "soft" one (0.03 MPa). It can be seen that it is possible to change the dissipation characteristic. The difference, in this case, is about 66%. Additionally, Fig. 20 shows that it is possible to regulate the maximum load that is transferred to the impactor object. Figure 20 shows that, in the case of a crash into the rigid post, the car bumper was damaged, as is visible from the high plastic deformation. When the vacuum pressure inside the parking post was lower, the car was not damaged to the same extent and could still be driven.

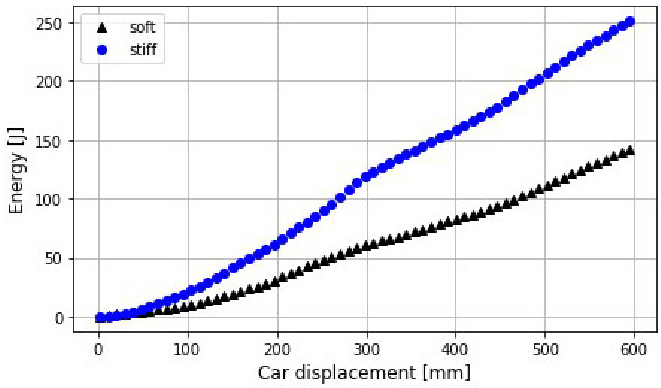

Fig. 20. Energy in the function of car displacement

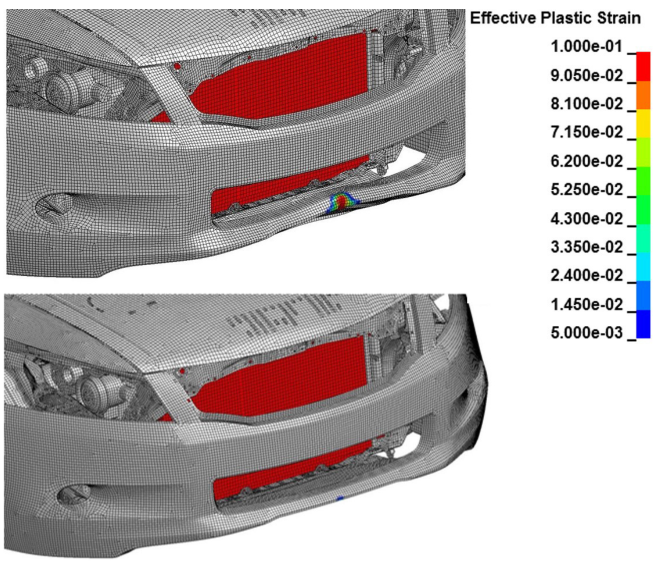

Fig. 21. Equivalent plastic strain in car bumper ("stiff" parking upper, "soft" lower)

It should be remembered that this analysis was performed only for the one crash scenario, and certain further work is required to make sure that this object functions correctly. However, the experiment does prove that by changing the vacuum pressure it is possible to regulate the maximum load that is transferred to the car.

6. CONCLUSIONS

In this paper, a conceptual design for a crash energy absorber based on the granular jamming mechanism was proposed. A prototype structure was built and tested empirically. It was shown that, within the range of vacuum pressure of from 0.01 MPa-0.09 MPa, the energy dissipation changed by about 250% while the maximum force changed by more than 400%. The tests proved that the granular jamming mechanism, with its wide range of control, could prove to be very useful in crash energy absorption. This work also demonstrated the basic properties of VPPs and described a process for modelling them precisely. It was proved that it was possible to model even complex devices using the proposed modelling methodology. The simulations performed resulted in a very close correlation in energy dissipation capability, less than 2.5%. A proper modelling methodology makes it possible to start designing a potential application using VPPs in crash energy absorption – that of a parking post.

Based on the research presented here, it can be concluded that:

- By means of the vacuum pressure parameters, it is possible to control the dissipation of crash energy over a wide range using the granular jamming mechanism.
- VPP modeling using a modified Johnson–Cook model, called JC-p, makes it possible to predict the behavior of the material very well.
- A parking post could be a potentially attractive application of a smart absorber using the granular jamming mechanism, although further work is required.
- During the research work, some disadvantages of VPP structures were noticed that could limit the potential for being used in real objects, i.e. the low density of dissipated energy or limitations in the control speed of the device. Nevertheless, due to the simplicity of the material and the required control devices, it can be concluded that active absorbers using VPPs can be an attractive alternative to commonly available devices of this type.

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