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Short communication

Adaptive airbag system for increased evacuation safety

Rami Faraj *, Błażej Popławski, Dorian Gabryel, Tomasz Kowalski, Krzysztof Hinc

Institute of Fundamental Technological Research Polish Academy of Sciences, Warsaw, Poland

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ABSTRACT

This short communication is aimed at indication of a significant problem to be solved by researchers working in the field of engineering structures. The contribution concerns a very important application of a rescue cushion, which is an airbag system devoted to the impact mitigation appearing during evacuation of people from heights. Although, a very similar in the principle of their operation, car airbags have been thoroughly tested, rescue cushions have not received sufficient attention. It should be emphasized that the performance of the actually operated devices is far from sufficient and even fatal accidents occur. The authors identified the problem and have initiated a study, which includes numerical simulation and experimental validation of the impact absorption process, as well as the elaboration of a suitable adaptive solution.

1. Introduction

Rescue cushions may be classified as passive pneumatic energy absorbers, designed and applied specifically for the task of belaying falling persons. There are not many devices of similar construction and purpose. The most popular of them, which have made a huge industrial career, are automotive airbags. They were widely investigated in technical reports and papers on numerical simulations as well as experimental examination of their behavior [1]. Despite many years of research airbags are still under active development. One of the many innovative solutions is a pre-triggering system, providing increased occupant safety [2]. Scientific studies on possible negative effects of their misuse, such as in the case of children passengers [3], can also be encountered. It should be noted that the same threat applies to standard rescue air cushions – they work properly only within a certain predetermined range of dynamic conditions. Similar devices, however intended only for the individual protection, are some smart injury prevention airbag systems for pedestrians [4]. Pneumatic energy absorbers are also utilized in such highly demanding applications as vehicle suspension systems [5], landing systems for UAVs [6], adaptive vibration isolation [7], or even planetary landers [8].

Despite their undeniable significance for the society no effort has been made to investigate rescue air cushions in a systematic, scientific way. Their importance becomes clearly understood when one realizes that they are designed to alleviate the loads acting on people falling from heights, mitigating their negative effects and consequently saving lives of evacuated people.

The construction of the standard rescue cushion is very well established and was firstly officially described in 1989 by Peter Lorsbach in his patent application [9]. Each device of this type, produced by renowned manufacturers, has a very similar construction, faithfully mimicking the one described in the patent. Some deviations from the reference design seem to be very restrained and appear to be merely the ideas of the designers not supported by proper research, such as changing their shape from rectangular to hexagonal. We see a research gap in this field, and therefore we decided to take up this subject. Our main goal is to significantly enhance the energy absorption capabilities of the standard rescue air cushions by means of adaptation to different impact conditions and consequently reduce the loads acting on a falling person. We strive to achieve this by integrating controllable valve into the structure and taking into account strict operational requirements and constraints.

2. Problem formulation

The primary goal of a rescue air cushion is to minimize the negative effects of the impact resulting from an evacuated person landing on it. A number of quality indices is used in the automotive industry, including the classical head injury criterion (HIC). Similarly, the German norm DIN-14151 [10], which is devoted particularly to rescue cushions, specifies the maximum acceptable values of accelerations acting on head, chest and pelvis during the impact. These values cannot be exceeded for longer than $\Delta t = 3\text{ms}$. Within this study we consider one quality index for which the total force F, acting on the amortized object,

* Corresponding author at: Pawińskiego 5B, 02-106 Warsaw, Poland.
E-mail address: rfaraj@ippt.pan.pl (R. Faraj).

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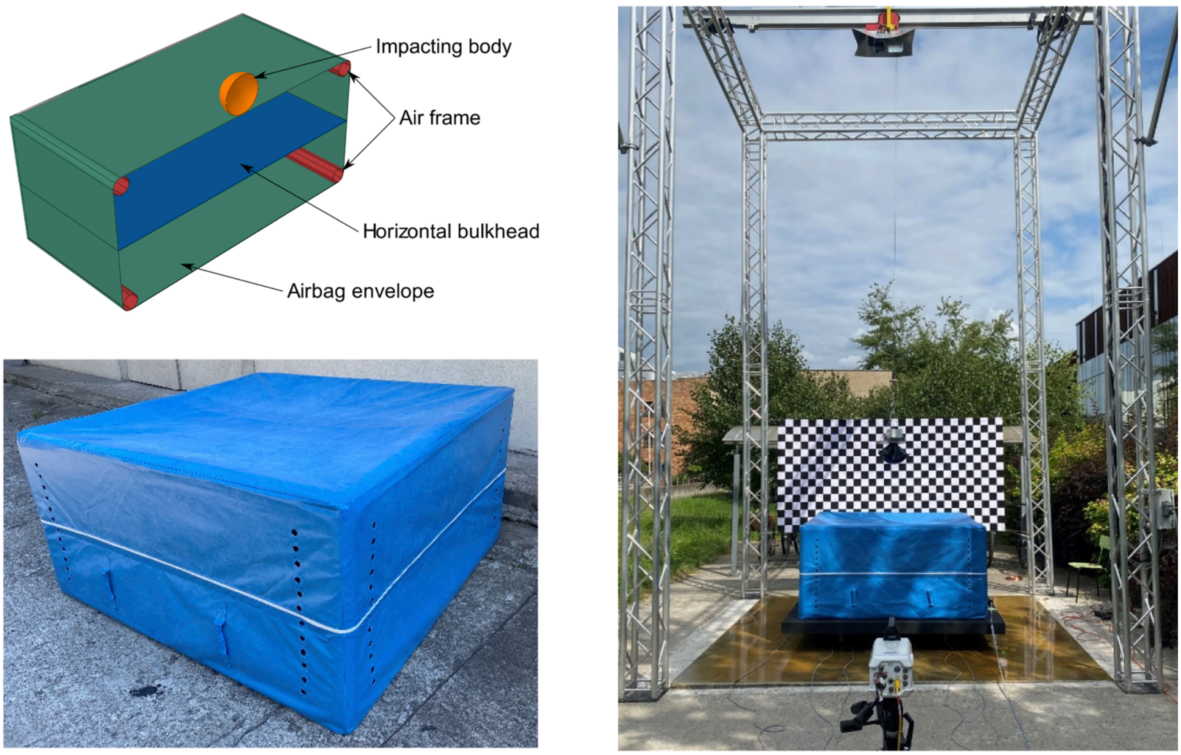

Fig. 1. The numerical model of a rescue air cushion, demonstrator in 1:2 scale and a dedicated drop stand during experimental tests.

is taken into account. Due to mechanical properties of the impacting object utilized in the experimental study, the minimization of total force may be considered as an equivalent to minimization of decelerations. The aim of the optimization procedure is to find the venting area A_v which will ensure that the highest level of the total force F, exceeded for no longer than a time period Δt, is minimal:

$$\text{Minimize } \max_{t_i}\left(\min_{t\in\left[t_i-\frac{\Delta t}{2},\, t_i+\frac{\Delta t}{2}\right]} F(A_v, t)\right) \tag{1}$$

with respect to $A_v \in \left[A_v^{min}, A_v^{max}\right]$.

3. Rescue air cushion device – modelling, simulation and experimental validation of the numerical models

To our knowledge, no systematic analysis of the pneumatic absorber in the form of a rescue air cushion has been conducted to date. As our research is highly motivated by the practical application, we started our investigations with both numerical simulations and experimental testing, which were supplemented by a cooperation with fire brigades. Computer analyses include development of a FEM model, while experiments are conducted using a dedicated drop stand and a lab-scale demonstrator, both presented in Fig. 1. This approach allows us to incorporate and test new design ideas in the most efficient way.

To reliably model the behavior of the device, at first the material characteristics of the experimental airbag were tested. Membranes of the rescue cushion has been manufactured using a dedicated material based on Polyester weft and Hypalon warp. Mechanical parameters of this material have been identified using the MTS-242 test stand, equipped with stereographic fast cameras, digital image correlation software and strain computation system ARAMIS. Tensile tests were performed for a number of samples to ensure the reliability of the results. This also proved a good repeatability of the experiments and allowed to estimate the force-strain characteristics. They were obtained for two perpendicular directions, according to the spatial orientation of weft, and

Table 1
Parameters of the manufactured, laboratory scale, rescue air cushion.

$M_{resc.\ cush.}$ [kg]	H [m]	A [m]	⌀ D [m]	A_v [mm^2]
10.37	0.85	1.75	0.1	33 250

implemented in the numerical model of the rescue cushion system as a special woven fabric material. Such material model is utilized extensively in automobile airbags modelling. The elaborated model was discretized using the first order membrane finite elements. Our FEM model accounts for the fluid–structure interaction in a simplified manner by means of the unified pressure method in which the fluid is modeled as an ideal gas with characteristics, such as its density or pressure, uniformly distributed across its whole volume. In order to validate the elaborated numerical models the dedicated drop stand has been established. According to Fig. 1. it is based on the prefabricated truss sections, beam with an overhead crane and hoist. As a result, a free fall of the impacting object from height of up to 6.5 m can be conducted. The rescue cushion can be impacted centrally from different heights or outside its center to check the system's stability. Four force sensors are installed beneath the lightweight composite plate. The state of the rescue cushion is registered using differential pressure sensors in both chambers of the airbag and an absolute pressure sensor mounted in the airframe. Ambient pressure measurements are also collected during the drop tests. The data acquisition is conducted using NI CompactRIO systems, whereas the control is conducted via a PLC integrated with remote control modules.

The laboratory demonstrator of rescue air cushion is manufactured as a cuboid with a square basis of side length A, height H and the diameter of the air frame ⌀D. Mass of the entire system is equal to $M_{resc.\ cush.}$. Side walls of the airbag are equipped with 24 vents of 21 mm diameter each, providing the overall venting area equal to A_v. The horizontal bulkhead is mounted in the middle of the cushion's height. All above mentioned mechanical and geometrical parameters of the system are collected in Table 1.

Fig. 2 presents a comparison of the reaction forces acting on the plate

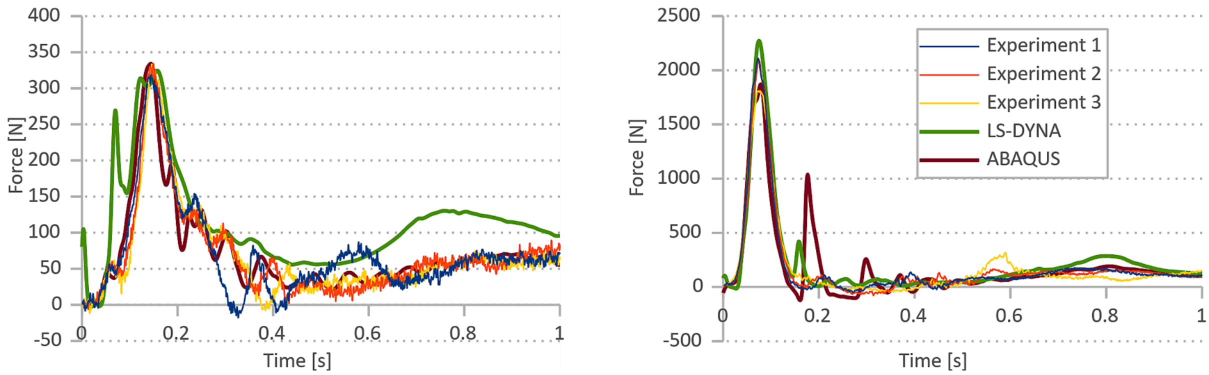

Fig. 2. Comparison of numerical and experimental results in two selected cases: (a) m = 5.7 kg, v_0 = 2.53 m/s (h = 0.33 m), (b) m = 10.7 kg, v_0 = 6.96 m/s (h = 2.47 m).

during experimental tests and obtained in numerical simulations using LS-DYNA and ABAQUS software environments. The left graph presents results in case the mass of impacting body is 5.7 kg and its impact velocity is 2.53 m/s, while the right one compares system's response obtained for the mass and velocity equal to 10.7 kg and 6.96 m/s respectively. As shown on the graphs, two independently developed numerical models have been elaborated and validated successfully – the highest force peaks, which determine the impact mitigation performance, correspond to the values obtained in experimental tests for two completely different excitation conditions. Therefore, they can be used for determination of the adaptation procedure providing a safe, sub-optimal operation of the rescue air cushion. Additional force peaks appearing in numerical simulations result from the specified contact conditions and impacts of the rescue cushion's side edges against the plate, which is not observed during experimental tests.

4. Novel adaptive rescue cushion

Considering specific characteristics of the evacuation processes conducted by fire brigades and the requirements of high system reliability, it is assumed that adaptation of the rescue air cushion is conducted based on the data provided by its operator. In order to properly design and program the adaptation mechanism a statistical study on a group of firefighters has been conducted. Within each experiment the firefighters were supposed to measure the evacuation height using an optical rangefinder. Obtained measurement accuracy has been described in terms of the mean value of the estimation error and its standard deviation. Assuming the normality of the distribution of the statistical process generating samples (determination of the impact parameter by the firefighters), the 3-sigma rule is used to ensure that 99.7% of all possible outcomes are considered. Fig. 3 shows the average and extreme estimations, as well as the envelope of 3-sigma rule outcomes.

During above statistical experiments firefighters were also asked to estimate mass of different people. Obtained results showed that typically estimation error does not exceed 25%.

It is assumed that the response of rescue air cushion is adapted just before the impact by using dedicated valves, which change the venting area A_v and the corresponding mass flow rate. The ranges of impact parameters, which are both the height of evacuation h_e (related impact velocity v_0) and the mass of landing person m, are divided into arbitrary adaptation ranges as shown in Fig. 4. Exemplary adaptation ranges can relate to the percentile grid of the society and take into account adaptive capabilities of applied valves. Selected adaptation ranges are a main part of the optimization ranges, which are obtained by adding buffers determined by levels of estimation accuracy at the ends of adaptation ranges. The optimization ranges are overlapping, what guarantees that calculation of proper valve openings is conducted in a safe manner. As

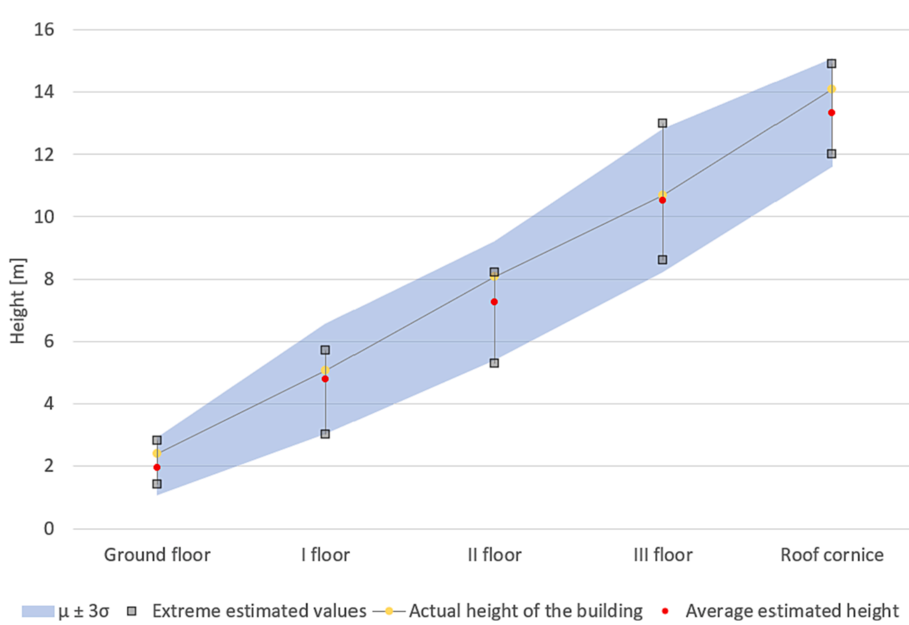

Fig. 3. Results of a preliminary statistical study on accuracy of evacuation height estimation by firefighters.

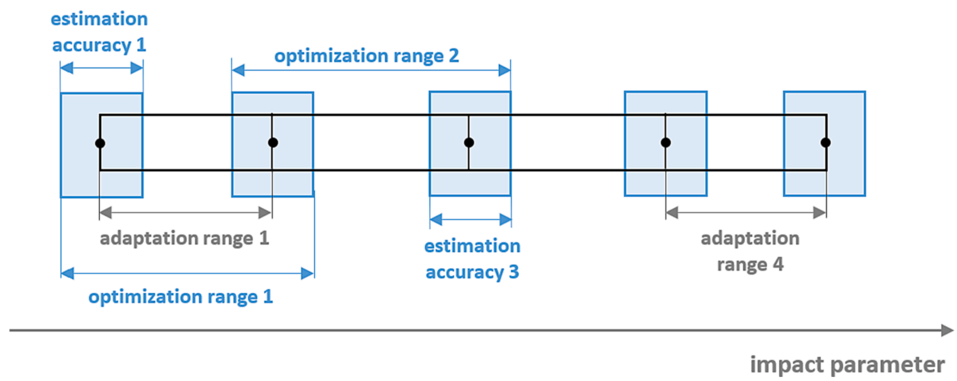

Fig. 4. Optimization strategy for the applied adaptation technique.

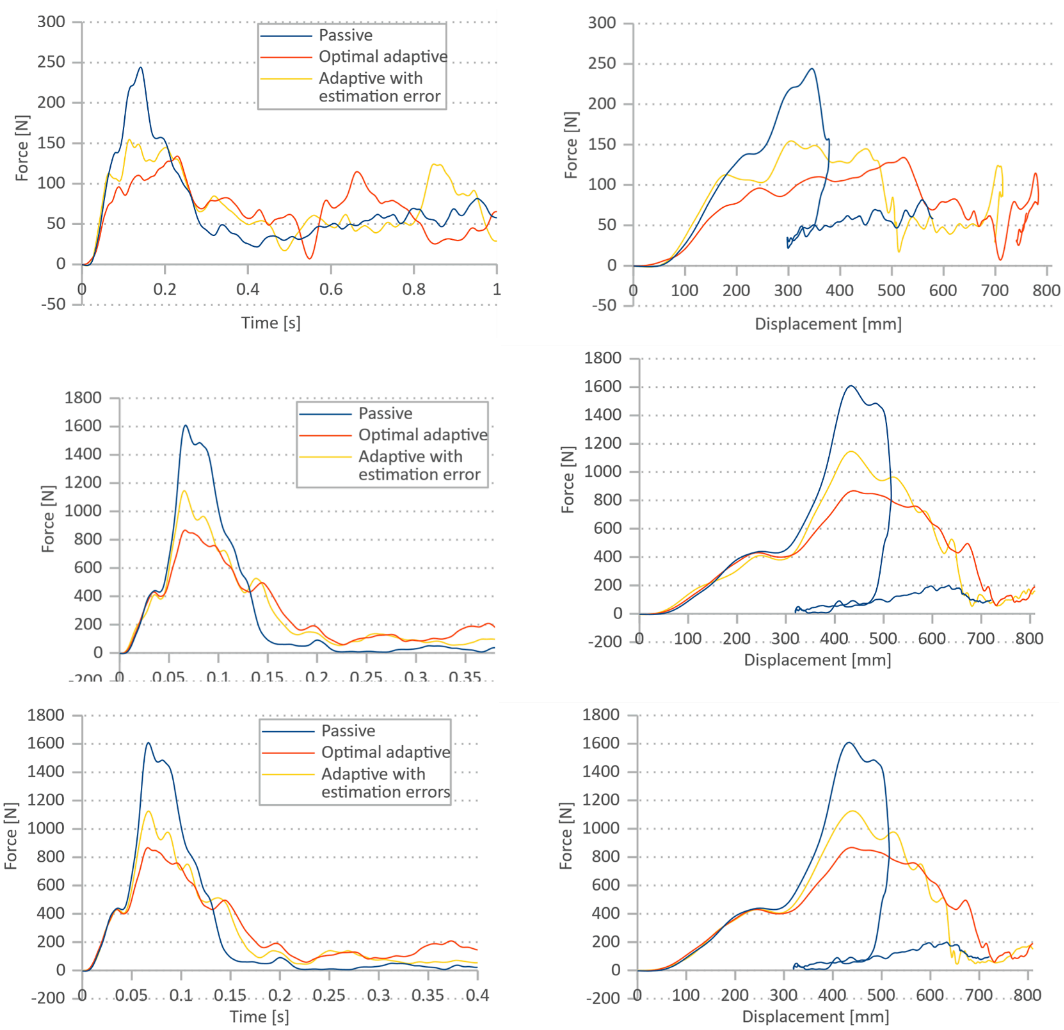

Fig. 5. Comparison of passive and adaptive system with and without estimation errors in three cases: first line – m = 5.7 kg, v_0 = 2.53 m/s, 30% velocity error; second line – m = 10.7 kg, v_0 = 6.96 m/s, 25% mass error; third line – m = 10.7 kg, v_0 = 6.96 m/s, 25% velocity and mass errors.

a result, the possibility that estimation error will cause incorrect adaptation of the rescue cushion is eliminated.

In order to demonstrate the effectiveness of the adaptation method a number of numerical simulations have been conducted. Within this numerical study the validated model, which is discussed in Section 3, was utilized and the estimation errors corresponding to 30% difference of impact velocity and 25% difference of mass were considered. Effects of adapting the rescue air cushion to the impact velocities $v_0 = 2.53$ m/s and $v_0 = 6.96$ m/s (experimentally registered cases, see Fig. 2) are shown in Fig. 5. The graphs present system response in three cases: (1) impact velocity is estimated with 30% error, (2) mass is estimated with 25% error, (3) above velocity and mass estimation errors appears simultaneously. As expected, for all cases the obtained performance is much better than in the original, passive case, where the airbag is

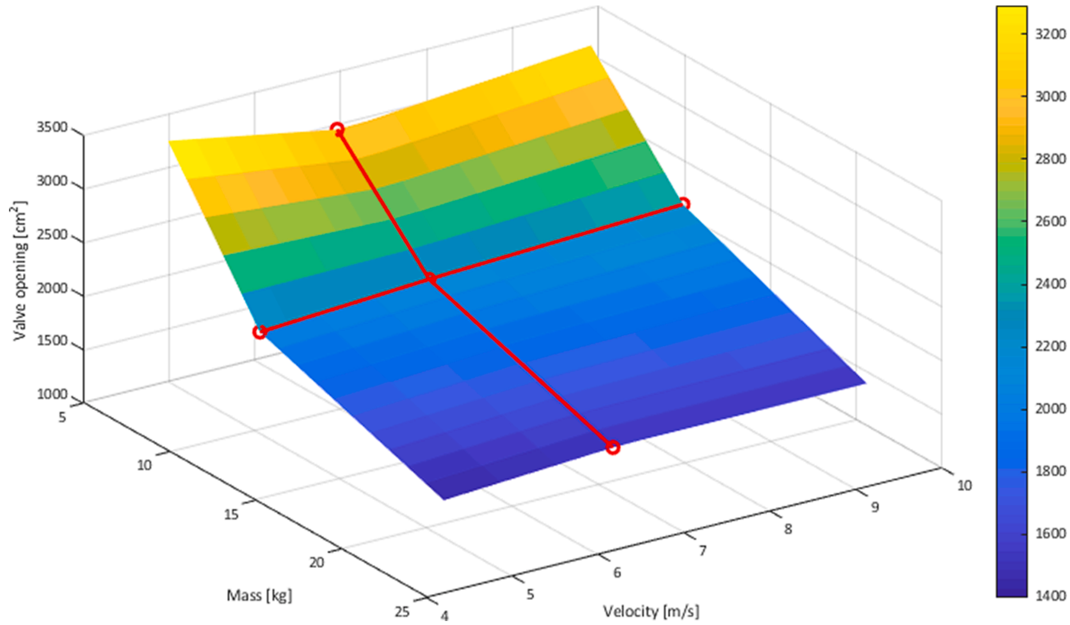

Fig. 6. Optimal venting area as a function of velocity and mass.

typically designed for the worse impact conditions. Within considered ranges of impact parameters inaccurate estimation of landing person's mass has bigger influence on optimality of the obtained reaction force than the velocity error. It is proved by two facts: reaction force in case of mass error is increased more than in case of velocity error; system performance in case both errors appears is comparable with the case of only mass error. In the case where no estimation error occurs the system response is better, but the difference is not very pronounced. According to this fact, it can be concluded that performance of the proposed adaptation method utilized under estimation of impact parameters' errors is very close to optimal.

For completeness of the study a number of optimization analyses have been conducted in order to determine the best venting areas ensuring optimal impact mitigation. In Fig. 6 obtained optimal values as a function of impact velocity and impacting object mass have been shown. Optimization was conducted for nine combinations of velocity and mass. Values of optimal venting area for remaining combinations were interpolated linearly. Within the graph five calculation points have been selected and signed with red markers. These points correspond to three levels of impact energy obtained for different values of velocity and mass. As a result, two important facts have been revealed. Firstly, the influence of impact velocity and mass on optimal venting area can be opposite. Secondly, the optimal venting area depends on combination of impact parameters (velocity and mass) – optimal value for the same impact energy may differ depending on exact values of both parameters.

5. Conclusions

The paper indicates a significant problem, which is very important from the practical point of view and should be addressed by the researchers working in the field of engineering structures, in particular adaptive impact absorption. The contribution consists of formulating a new problem and presenting a general framework, which is applied by the authors to solve the problem and make evacuation operations safer. Numerical models of the airbag system, which have not been published by any researchers to date, were developed by the authors and outlined at the beginning of the article. Novelty of the presented research can be found also in the proposed adaptation method, which includes consideration of the accuracy of the impact parameters' estimation. At this point the authors hope to get interest of the researchers over the world to develop the best possible solutions and save many human lives.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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