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On optimization of an adaptive pneumatic impact absorber – the innovative rescue cushion

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Abstract. The paper states a complex study on the adaptive rescue cushion and concerns a problem of efficient impact mitigation, which is present during evacuation or assurance of people conducted by fire brigades. In order to minimize negative effects of person's fall from height an airbag system is applied. Unfortunately, until now only passive solutions have been used. As a result, loads acting on a landing person were not minimized, because passive systems are designed for predefined, extreme conditions. Since the authors proposed to introduce adaptation mechanisms into the rescue cushion, a number of issues arose. They include construction and control of release vents, taking into account the inaccuracies of estimated impact parameters, and optimization of the venting area in case the evacuated person lands outside the airbag's center. All these problems were addressed within this paper and described in detail. Discussion on the system adaptation and its optimization was preceded by experimental validation of a numerical model. The energy absorbing capabilities of widely used passive rescue cushions were significantly enhanced as a result of the conducted research.

Key words: adaptive airbag, Adaptive Impact Absorption, inflatable structure, pneumatic absorber, rescue cushion

1. INTRODUCTION

Impact mitigation problems constitute an important issue in terms of safety science and research. Accidents caused by mechanical impacts are ubiquitous and can be found in the workplaces [1, 2], as well as on roads, where barriers [3] and car airbags are applied for people protection in case of crash [4]. In order to significantly reduce or avoid human injuries, various protective solutions are used. In accordance with falls from heights, which are the problem addressed within this study, protective devices include the fall arrest systems [5] applied to avoid harsh contact with the ground, as well as the impact absorbing devices, such as rescue cushions (see Fig. 1). A rescue cushion, called also a safety cushion, is an airbag system applied by fire brigades for evacuation and assurance of people at height [6] in order to minimize loads acting during landing of people on the airbag. As a result, the probability of injuries or death can be significantly reduced. Due to the fact that rescue cushions are classified as a rescue equipment, they have to meet a number of technical and operational requirements, which include among others limited self-weight, compact size, short time of preparation, simplicity of maintenance and reliability. Moreover, rescue cushions have to operate successfully for wide range of impact parameters. As a result, their mechanical response is strictly constrained and far from optimal. High values of decelerations can intuitively be expected when the typical height of safety airbag is assumed at the level of 170 cm. It leads to relatively high decelerations, which from physical point of view cannot be lower than 10 g in case the jump height is 16 meter. In practice the decelerations are much higher due to a constant value of venting area, which moreover, is selected to the worse possible case of impacting object's mass, indicated in official requirements at the level of 150 kg.

Fig. 1. Rescue cushion operated by Polish fire-fighters (source: National Headquarters of the State Fire Service of Poland)

Airbag systems applied for impact mitigation can also be classified within a group of shock-absorbers. Shock-absorbers typically utilize passive or semi-active absorption and dissipation of the impact energy. Depending on the application we can find pneumatic absorbers, e.g., airbags [7], gas double-chamber cylinders [8, 9], hydraulic [10], frictional [11] or particle-based [12, 13] dampers.

In order to provide possibility of shock-absorber's control they had to be equipped with electronics, sensors and controllable actuators. As time periods present in impact mitigation processes are very short, typically not exceeding hundreds of milliseconds, extremely fast mechanical systems have to be applied for real-time control, e.g. piezo-electric valves [14]. Based on such actuators semi-active control methods [15, 16, 17] have been already proposed and proved to be efficient. Very high speed of system operation is obtained at the price of low range of achievable displacements, what make such solutions inapplicable for adaptation of rescue cushion

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system, because it requires high changes of the airbag's venting area. Alternatively to a very challenging real-time control, the so-called 'semi-passive' adaptation technique can be used [18]. In such a case the impact parameters are predicted just before or at the very beginning of the excitation process. Then, the system is reconfigured, taking into account actual loading conditions. After that, the system operates in passive manner but it is adjusted to the impact conditions. This reconfiguration technique was applied for adaptation of the rescue cushion presented in this manuscript.

Safety devices utilized for amortization of people falling from heights have been developed and used for many years. The first widely recognized cushioning device was the net patented in 1887 by Thomas F. Browder [19, 20]. This device quickly gained popularity and successful evacuations attempts were reported. In the interwar period of the twentieth century, rescue blankets, also known as rescue sheets, appeared [21]. In Europe, rescue sheets have even been standardized in DIN 14151-T2 [22]. Unfortunately, due to the emerging accidents and large number of people required for service, it was not a popular device. The next step in the field included invention of the first rescue cushion by John Tom Scurlock in 1973 [23]. A fan-driven airbag was inflated with air to safely absorb the impact of a man's body falling from height. This rescue cushion had two parts: the lower one with a higher pressure and a smaller area of the discharge holes, and the upper one with higher ability of gas release. At the end of the 80s of the last century, another type of a rescue cushion was invented, commonly known as a pneumatic frame rescue cushion. Its inventor was Peter Lorsbach [24], whose solution was characterized by relatively high mobility, good amortization, short preparation time and small number of people required for system operation. It is currently the most widespread type of a rescue cushion in the world except the United States, where fan-based rescue cushions are the most popular.

In the following years, the design of rescue cushions did not undergo any significant modifications, and the general principle of their operation has remained unchanged to this day. Most of the currently constructed rescue cushions comply with the German standard [25]. However, there were some developments going beyond the general requirements specified in the norm. In 2004 Manfred Vetter proposed a division of the landing area into several circles of different colors (blue and white), which were supposed to have a calming effect on people forced to jump [26]. Another innovation was equipment of the pneumatic frame with an air pressure control device, which was based on compressed air sensor and a display directed to the user [27]. Next novelty improving the safety of rescue cushions' use was the invention of a cover for a compressed air cylinder supplying the pneumatic frame with operational gas [28]. In addition, it is worth mentioning the works on implementation of lighting for rescue cushions as well as modifications of airbag characteristics adjustments of the size and number of venting holes. The authors take the step further and optimize the rescue cushion response under various impact conditions by using original adaptation technique [6] and implementing semi-passive valves, which were submitted for patent protection [29]. As a result, the innovation discussed in this manuscript constitutes a significant contribution to the safety science field. In comparison with a preliminary study in [6], where only general framework for system adaptation was introduced, content of this manuscript covers detailed discussion on problems not analyzed previously. The main contributions are experimental demonstration of the adaptive system and complete analyses of various aspects including influence of impacting body's shape and position of impact.

2. IMPACT MITIGATION PROBLEM AND ADAPTATION STRATEGY

2.1. Problem formulation

The primary goal of our research was to mitigate loads acting on a person landing on a rescue cushion. We wanted to achieve this by introducing adaptive capabilities to this device, but firstly we needed to specify this objective in a quantitative manner. This allowed us to analyze and compare the obtained results with a simple routine.

As a result of the mechanical impact corresponding to landing on a rescue cushion, a human being is subjected to excessive decelerations. Resultant force acting on a person is the de facto pneumatic force arising in the cushion's chamber. Since this phenomenon is very similar to the case of a car passenger hitting an airbag during an accident, we can take into account some well-specified coefficients developed to measure and compare different impact conditions. One of the most widely used quality indices, regarding the influence of the impact on human body, is the Head Injury Criterion (HIC), adopted especially in automobile crash tests [30]. It is a measure proposed by Versace [31] and taken on by National Highway Traffic Safety Administration (NHTSA) [32], which takes into account both the level of deceleration and its duration:

$$HIC = \max\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\}, \quad (1)$$

where acceleration is measured as multiples of the standard acceleration due to gravity (g) and time is measured in seconds. It gives the values which can be mapped to probabilities of suffering injuries of different severity, based on the historical experimental data.

According to Eq. (1) HIC is defined as a maximum of the weighted mean deceleration (square brackets) calculated in time interval $\Delta t = t_2 - t_1$ and multiplied by its duration. Maximum width of time window is set to 36 ms, as proposed by the NHTSA [32]. This value emerged after examination of available test data at that time. In 1999 NHTSA proposed evaluation of HIC over a 15 ms time interval what became a de facto standard.

German standard DIN 14151-3 [22], one of the very few devoted to rescue cushions, describes maximal values of accelerations to which certain parts of the human body can be subjected: head – 80 g, chest – 60 g and pelvis – 60 g (g = $9.81\,\mathrm{m/s^2}$). Accelerations higher than specified in the standard cannot act on a human body for longer than 3 ms. This specific

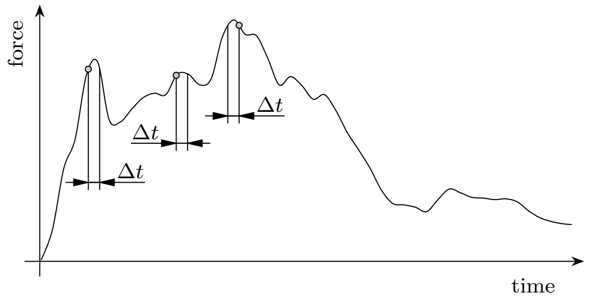

Fig. 2. Determination of a maximum force – value which is exceeded for longer than the assumed time period Δt

duration comes from the assumption that accelerations lasting shorter do not have any effect on the human brain [33]. For longer durations, more than 30 ms and up to 100 ms, a constant load of 40–50 g can be considered safe for a human [31].

Based on the information provided above we developed a quality index utilized in the optimization procedure. The goal was to minimize the maximum reaction force acting on a person hitting the rescue cushion while taking into account the condition on a force impulse duration. This goal was visualized in Fig. 2 and defined mathematically in Eq. (2):

$$\text{For estimated } m, v \text{ minimize:}$$
$$\max_{t_i}\left(\min_{t\in\left[t_i-\frac{\Delta t}{2},t_i+\frac{\Delta t}{2}\right]} F(A_v,t)\right), \tag{2}$$
$$\text{with respect to } A_v \in \left[A_v^{min}, A_v^{max}\right].$$

In order to conduct the optimization, some basic parameters of the falling object have to be identified – its mass m and impact velocity v at the moment of touching the landing surface. Once parameters' estimation is done, adjustment of the venting area – A_v – of the rescue cushion is utilized as a control function to minimize the maximal force acting on a landing object – $F(A_v,t)$, in particular a person. Consideration of the minimum acceleration pulse length is expressed by the innermost part of the minimization – setting Δt to 3 ms and seeking for the minimal value in the time window which is swept through the whole time-domain signal.

2.2. Adaptation technique

Optimization problem formulated in Sec. 2.1 was considered as ideal case which never could be met in real-life applications. In the case of adaptive rescue cushion there are several sources of inaccuracies introducing distortions to the presented algorithm, both internal and external ones. As the structure is constructed with membrane sheets, shape of which is maintained with the pressurized frame, some unforeseen inaccuracy of shape may occur leading to a different volume of air available for compression within a pneumatic airbag. Also, the actuators controlling the venting area may be set inaccurately due to an error on the encoder. Depending on how the impact parameters are identified – automatically by some additional equipment of the device, i.e. sensors or cameras with embedded computer, or by the operator relying on his intuition as to the correct assessment of the object's mass and height at which it is placed – estimation inaccuracies may vary significantly. The magnitudes of possible errors had to be taken into account within the developed adaptation technique to ensure better performance than in the case of a passive rescue cushion. Despite the extraordinary features, the adaptive rescue cushion must still meet a basic condition, expressed in national standards and regulations, which means avoidance of the ground hitting by a person (dummy during certification) landing in the center of the rescue cushion under any impact conditions.

Mass and velocity estimation errors are the ones that have the greatest impact on the dynamic response of the rescue cushion and they can be feasibly considered within the adaptation technique, by modifying Eq. (2) and introducing an additional term:

$$\text{For estimated } m, v \text{ minimize:}$$
$$J_{kl} = \max_{\substack{m\in[m_k-\delta,m_{k+1}+\delta]\\ v\in[v_l-\varepsilon,v_{l+1}+\varepsilon]}}\left(\max_{t_i}\left(\min_{t\in\left[t_i-\frac{\Delta t}{2},t_i+\frac{\Delta t}{2}\right]} F(A_v,t)\right)\right),$$
$$\text{with respect to } A_v \in \left[A_v^{min}, A_v^{max}\right]. \tag{3}$$

Safety measures taken to make the optimization procedure secure for the landing person are represented by the first maximization term in Eq. (3). This expression incorporates two proposed solutions: 1) dividing the optimization space (m,v) into adaptation areas; 2) enlarging these areas by estimation accuracy levels δ and ε leading to overlapping of adaptation areas, what is presented graphically in Fig. 3 (left). For instance, if we consider adaptation area no. (k,l), which corresponds to the range of masses $[m_k, m_{k+1}]$ and the range of impact velocities $[v_l, v_{l+1}]$, the optimization done by solving problem (3) is conducted for following ranges of impact parameters: $[m_k-\delta, m_{k+1}+\delta]$ for the mass and $[v_l-\varepsilon, v_{l+1}+\varepsilon]$ for velocity. It means that, even if impact parameters are close to the limits of particular adaptation area and some estimation error occurs, the obtained opening area of the vents is safe. Performance of the airbag is of course worse than in the case when the estimation accuracy levels are not included in the optimization process, but in case of inevitable inaccuracies such approach is reliable and guarantee avoidance of person's hitting the ground due to too large valve opening.

Extending the optimization procedure to include this term means that the maximum force pulse lasting longer than a certain specified time period is still looked for, but now the largest value in a predetermined bounded parameter space is sought and taken as representative of that area.

Both of the proposed solutions are intended to mitigate possible estimation errors and can be considered as a safety layer added to the original optimization procedure. Dividing the optimization space into a finite number of regions of interest takes into account the limited perceptual capabilities of the human operator, as well as the estimation error, conducted either by a human or by a computer. They must be adjusted to the specifics of the utilized rescue cushion, in general its size, and impact parameter's estimation method. Extra offsets (δ, ε), included in the adaptation procedure, allow for choosing the

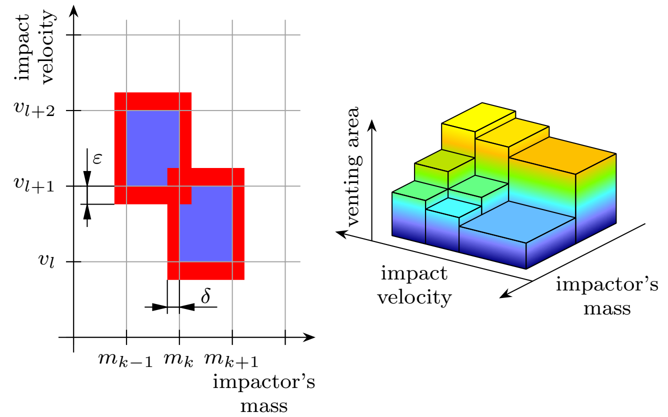

Fig. 3. Scheme of impact parameters' division into adaptation areas (left) and corresponding vents opening areas (right)

best solution in the case of uncertainty, when estimated parameters lie on the border of the designated adaptation areas. Their values also have to be specified based on the identified estimation errors. Exemplary results, in the form of the venting area A_v, of the described procedure are presented in Fig. 3 (right). In each of the designated adaptation areas the lowest venting area, corresponding to the highest pneumatic force generated and lowest probability of hitting the ground, was found.

Allowing estimation accuracy areas to overlap entails the need to consider cases in which estimated parameters lie on a point belonging to even up to four of them (see point m_k, v_{l+1} in Fig. 3). Following the safety principle described earlier, in such a case, it is necessary to select that adaptation area which indicates the smallest venting area. This adds another layer of optimization to the procedure described for finding the best values of venting areas, which is, however, very simple:

$$\begin{gathered}\text{For estimated } m = m_k \text{ and } v = v_l \text{ find:}\\ A_v(m_k, v_l) = \arg\min\{J_{k,l}; J_{k+1,l}; J_{k,l+1}; J_{k+1,l+1}\}.\end{gathered} \tag{4}$$

Eq. (4) states that in the special case where the estimated mass and impact velocity turn out to represent a point belonging to four estimation accuracy areas, the smallest venting area of the four should be chosen as the output variable.

Eqs. (3) and (4) combined constitute the adaptation technique developed to optimize the characteristics of the rescue cushion.

3. DEVELOPMENT OF THE ADAPTIVE RESCUE CUSHION

As mentioned above, rescue cushions are the devices saving human lives. For this reason, their design process must ensure very high reliability and consideration of every possible use case. Since these devices must meet the conditions described in national standards regarding such aspects as their maximum weight or landing area, most of the produced models are very similar in shape and performance. In view of this state of affairs, the rescue cushion proposed by the authors also has a design which is very similar to the others – a cuboid one. It is a layout that has been tested under a wide range of operational conditions over the years, so it can be considered to meet the standards imposed by the regulators. What makes it stand out is its adaptability, which is obtained due to the use of controllable valves.

Development of the rescue cushion presented in this manuscript was performed in two ways – experimental and numerical, which made it possible to test a number of proposed solutions in a relatively short time while ensuring that the generated results are close to the solutions obtained in practice. A geometrically scaled demonstrator with a typical cuboid shape was manufactured from materials utilized in the production process by one of the rescue cushions' producers[1]. It allowed us to conduct test drops, on the drop tower built especially for this purpose, using different types of impactors adapted for this particular task, e.g. balls, plates or specially designed dummies (see Fig. 4). A Finite Element Method (FEM) model was created in Abaqus software environment. Numerical simulations were performed in Abaqus/Explicit utilizing its Hydrostatic-Fluid-Mechanical Multiphysics (HFM)[2] capabilities in order to include interactions between the walls of the airbag and the air filling the enclosed cavity. It was validated for the chosen boundary conditions and utilized in the optimization procedure, striving for the best dynamic response in all possible impact conditions.

Every popular model of the rescue cushion is equipped with a set of vents on its side walls, similar to those visible on the wall of the rescue cushion presented in Fig. 1. The airbag presented in Fig. 4 is equipped with similar vents, however their instrumentation allows for changing their effective venting area influencing the pneumatic characteristics of the rescue cushion during impact.

3.1. Semi-passive valves

The considered adaptive rescue cushion is based on an airbag of cuboid shape and it is equipped with release vents located near side edges of the airbag (see Fig. 4). According to operational and reliability requirements, control of venting area has to be conducted in as simple as possible way. Such need is reflected in Fig 5, which presents the general scheme of the adaptive system operation. It includes three consecutive steps. The first one is related to identification of impact parameters, which in particular consist of landing person's mass and velocity. Due to the fact that any mechanically controlled vents possess limited speed, it is necessary to conduct estimation of impact parameters before the body contacts the airbag, preferably before the jump. After that the selection of the appropriate vents opening is performed by utilizing proposed adaptation method. Finally, vents are adjusted to the set values of venting area, which takes into account estimation inaccuracies as indicated in previous section. In order to implement such strategy, the authors invented a system of vents, where their opening is obtained by moving special shutters to the desired position. Control of shutters' movement in the laboratory demonstrator

[1] Scale factor 1:2 when compared with a typical rescue cushion designed to save people jumping from up to 16 m.

[2] This is also called the Unified Pressure Method (UPM) in other software environments.

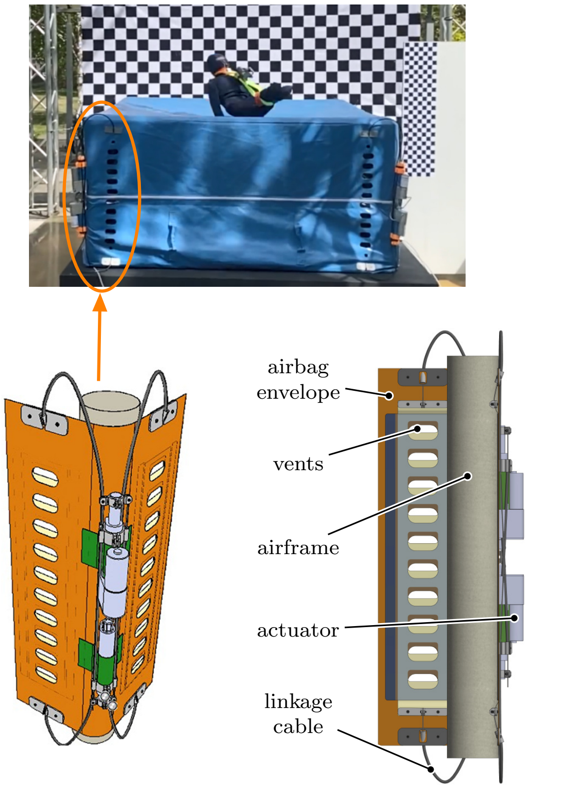

Fig. 4. Demonstrator of the rescue cushion with adaptive valves system during drop tests and CAD model of the valves

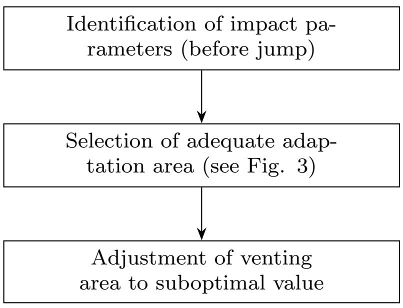

Fig. 5. Operation of the system

was realized using two opposite-oriented actuators. Thanks to such solution, a proper position of the shutter relative to vents in the airbag is obtained. One actuator pushes and the second one pulls the shutter. In this way possible jams of the shutter are avoided. Within a patent application submitted by the authors some alternative solutions, where for instance the actuators are replaced by a system of springs and rotary drive winding/unwinding the shutter to/from spools, are presented. Independently from the applied actuation system, movement of shutters relatively to the airbag envelope allows to control the overlapping area, which is created by holes cut in shutters and in the airbag envelope. The minimum effective venting area relates to completely closed valves – no overlapping of holes in shutters and rescue cushion envelope. In turn, the maximum venting area is limited by the size of the holes in the airbag envelope.

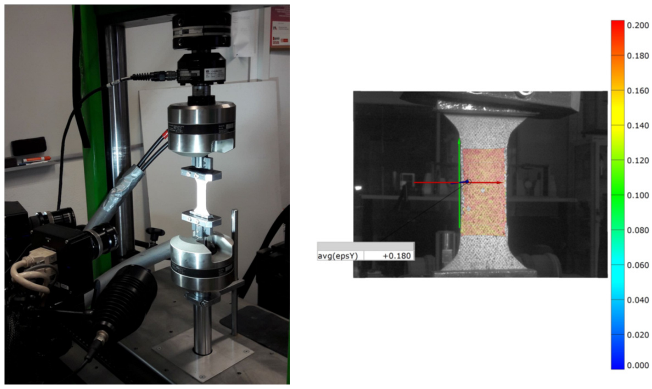

Fig. 6. Experimental setup and Digital Image Correlation analysis example

3.2. Experimental tests and model development

Building a reliable numerical model must be conducted on the basis of experimental studies that serve as a source of input data and for the subsequent validation of the developed model.

3.2.1. Identification of the fabric material mechanical properties

Goals and scope of the sub-study

In order to identify the mechanical properties of the cushion's material a series of tensile tests have been conducted. The key task was to determine the stiffness of the fabric in the two main directions of the weaving. Tested material, assigned by the manufacturer as MP-131, has been supplied in two types: regular weight and lightweight. Conducted study was also aimed at answering two questions regarding the material characteristics: 1) do textiles have comparable characteristics along weaving directions, and 2) do the two types of the supplied textile have similar mechanical properties and are fully replaceable. Finally, determined characteristics of the fabric material has been applied in the numerical model of the rescue cushion.

Methodology, test setup and results

Material testing was carried out in a uniaxial tensile test along the warp and the weft of the fabric on a servo-hydraulic load frame with the strain and axial load measurements (Fig. 6). Strains were calculated with a Digital Image Correlation (DIC) method by a stereographic optical system. Material samples were prepared from a brand-new portion of the material. Testing setup consisted of the following equipment: load frame with a servo-hydraulic actuator MTS 242.01, axial load cell MTS 661.19 of 5 kN capacity, stereographic set of digital cameras with Trinitar lenses 35 mm, DIC software Aramis by GOM. Samples were prepared with the following characteristic dimensions: 30 mm breaking width, 80 mm initial distance between the grips. Testing program parameters were as follows: grip velocity 0.1 mm/s, sampling frequency 2 S/s, measured signals: axial force, field strain on the sample surface.

The primary objective of the study could be fulfilled by determination of stress-strain curves for the tested materials. Representative strains in the direction of force application were

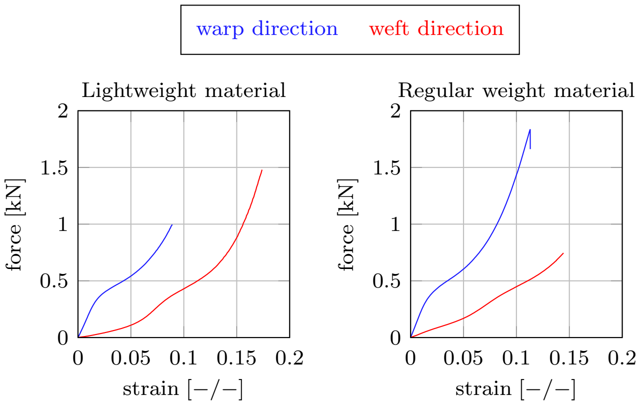

Fig. 7. Force-strain curves for the lightweight material (l.h.s.) and the regular weight material (r.h.s.)

calculated within a predetermined sub-region of each sample (Fig. 6). Determination of the stress values requires the knowledge of exact cross-section of the material. Due to the fact that the material is a composite and that the thickness of the material is not homogeneous because of the fabrication technique, the exact values of stress were difficult to estimate. For this reason, results of the study were depicted as axial force versus strain curves, which can be interpreted as a 'pseudo-stiffness'.

Experimental results were acquired in a procedure with three trials for each type of the analyzed material and direction. Therefore, the total number of tested samples is 12 (2 materials $\times$ 2 directions $\times$ 3 trials).

The force-strain curves, after averaging over trials, were determined for the further analysis. Fig. 7 depicts a comparison between the obtained characteristics dedicated to lightweight material (Fig. 7 left) and the regular weight material (Fig. 7 right). Each graph presents characteristics for two directions of the tensile testing (warp and weft).

The first finding is that the stiffness of the fabric differs significantly between the two weaving directions for both material types. The difference between the force-strain coefficient values is over sixfold and over tenfold for the regular weight and lightweight materials respectively. This scale of the variance makes it obligatory to take this parameter into account during an engineering design process. Furthermore, the stiffness of the two analyzed types of materials is in a comparable range. However, it must be noticed that the stiffness in the warp direction is 14% lower in the case of the lightweight material, whereas in the weft direction it is as much as 45% less stiff. The qualitative character of the difference is analogical for both tested materials. The stiffness difference is specifically demonstrated in the strain range between 0 and 0.01. The second finding is that the mechanical properties of both types of the material are comparable however not identical.

Obtained experimental results were analyzed in order to receive force-strain coefficients as a measure of stiffness, summarized in a tabular form (Tab. 1). The force-strain coefficient is defined as a slope of the force-strain curves defined for the range 0–0.01 of the strain. The unit of the coefficient is N. The coefficients are utilized for a comparative study of the particular types of the material.

Table 1. Force-Strain coefficients of the materials

	Regular weight material	Lightweight material
Warp direction	23.6 kN	20.2 kN
Weft direction	3.55 kN	1.93 kN
Warp/Weft ratio	6.6	10.4

The above presented study on the fabric material's mechanical properties revealed the following facts:

1. Materials exhibit significant differences in stiffness regarding the warp and weft directions. The differences are as high as sixfold in the regular weight material and tenfold in the lightweight material.
2. Materials are not fully substitutable between each other. The lightweight type of material is up to 45% less stiff in the weft direction in comparison to the regular weight one.

Based on the identified mechanical parameters of fabric materials the numerical model of the adaptive rescue cushion was elaborated and discussed in detail in the following part of the paper.

3.2.2. Finite Element Method model description

A typical rescue cushion is made of two structures – an airframe maintaining the shape of the cushion and an airbag envelope acting as a proper cushion. A Computer Aided Design (CAD) model of the structure utilized in numerical simulations is presented in Fig. 8.

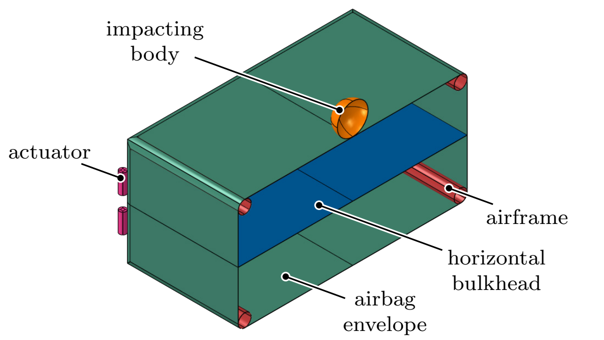

Fig. 8. CAD model of the developed rescue cushion (cross-sectional view)

Each separate part of the model in Fig. 8 is color-coded. In addition to the main components indicated above, this model consists also of a bulkhead (colored in blue) dividing the airbag horizontally into two chambers of the same height, models of vents' actuators (colored in magenta), the weight of which cannot be neglected, and the impacting body for the reference (colored in orange).

Each element building up a pneumatic airbag can be considered to work as a membrane, i.e., without any bending or transverse stiffness. Airbag envelope, airframe and the bulkhead were constructed from membrane finite elements, while vents' actuators, impacting body and the ground were chosen to be rigid bodies.

In real-life structures, the airframe and airbag envelope, as well as the horizontal bulkhead, are stitched, glued, sealed or zipped together on overlapping surfaces or edges, depending on the technique chosen by the manufacturer making it impossible for these elements to move relatively. This treatment was reproduced in the FEM model using tie constraints on edge regions and on the line where the airbag envelope intersects the edges of the horizontal bulkhead. Vents' actuators were also tied to the edges of the airbag. Another interaction phenomena to be accounted for was contact. It is important for the interaction in the normal direction between the upper shell and the horizontal bulkhead during the drop and between the lower shell and the ground. A general contact formulation available in Abaqus was chosen with a tangential Coulomb friction model. Friction coefficient was chosen arbitrarily to be equal to 0.3, what seem to be a good informed choice for the most probable environmental conditions.

A part of the system that had to be taken into account in the numerical model was the air filling both the airframe and the airbag. This significantly improved its complexity, since a Fluid-Structure Interaction (FSI) couldn't be neglected in this case. Abaqus allows for a relatively simple modeling of the FSI phenomena with its HFM capability. In this approach a fluid filling the cavity behaves like an ideal gas in the whole domain. It allows for mass exchange between the cavities and with the environment.

A special material model for simulating the behavior of such structures as automobile airbags or parachutes, which are made of woven fabrics, was utilized in our study. Its strength characteristics were chosen to mimic the behavior of the lightweight material described in Sec. 3.2.1. Thickness of the elements building the airbag and airframe was set accordingly to the averaged measurements taken on different samples of the woven fabric. Its density was chosen based on the measurements taken on the already produced elements – airbag and horizontal bulkhead. Density of the airframe material was set independently because its rubber warp was different than the one used for the airbag.

Finite element mesh generated for the model consisted of 144115 4-node membrane elements building the airbag, airframe and horizontal bulkhead, and 7532 4-node rigid elements building the impactor, ground and 8 vents' actuators.

The geometrical parameters of the model included airbag's height of 0.85 m, side length of 1.75 m and diameter of the airframe equal to 0.1 m. Weight of all fabric materials was 10.4 kg, whereas weight of adaptive valves with actuators was 8.8 kg.

3.2.3. Airbag dynamical model validation under impact conditions

The reliability of the results generated by the FEM model was ensured by validating it with experimental data obtained on the dedicated drop test rig. Experimental drop tests were performed for two different masses of the impacting body, which equaled to 5.7 kg and 10.7 kg, and three drop heights, corresponding to impact velocities of 3 m/s, 5.5 m/s and 7 m/s. The data acquisition system, which was based on NI CompactRIO, recorded the time history of the reaction force acting on the ground, as well as the overpressure in airbag chambers and inside the airframe. Each drop test was simultaneously recorded with a high-speed camera, allowing for a very accurate estimation of the impact velocity using the computer vision techniques. A frame from one of the captured recordings was presented in Fig. 9.

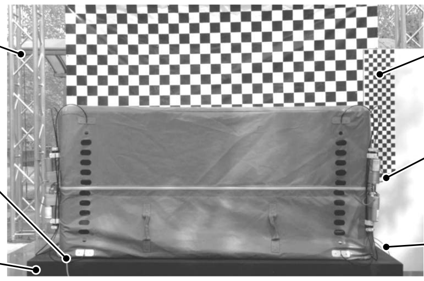

Fig. 9. Drop stand used for tests of adaptive rescue cushion – frame captured by a high-speed camera

The key elements of the drop stand were the ground plate supported on four force sensors based on strain gauges and the drop tower of 6.5 m height. For the purpose of velocity estimation, a tarp and board with a checkerboard pattern were positioned behind the rescue cushion and in the plane of the impacting body in order to eliminate perspective distortion error.

For each combination of the mass and height (impact velocity) two states of the valves were considered – entirely open or closed, what resulted in 12 different impact conditions. The drop for each combination of impact conditions was repeated three times to ensure the reliability of the obtained results. Reaction force and velocity of the impacting body were utilized for validation purposes.

Only one parameter of the FEM model was adjusted in order to obtain a satisfactory compliance between the experimental and numerical results – the total exhaust area from the airbag chambers (sum of vents opening areas and unknown leakages). The final results of the validation procedure were shown in Fig. 10 in the form of time courses of reaction force. Red lines in the figure presented the time courses for the vents-closed cases and the blue lines for the vents-open cases. Results of the experimental drop tests were presented with dashed lines and of the numerical simulations with solid ones.

Visual analysis of the results shows that the obtained compliance is very good. Only for the case (m1, h1) – the smallest mass and lowest height – there is a noticeable difference in the valves-closed case. This is not very alarming, as this case corresponds to the lowest possibility of injuries of the person landing on the rescue cushion.

It must be noted that the final venting area in the numerical model is significantly higher than the theoretical summarized area of the vents opening, present in the experimental rescue cushion. This can be attributed to unavoidable leakages at the bonding of fabric sheets (sewing or gluing) and the permeability of the fabric itself, which was not taken into account when the model was created.

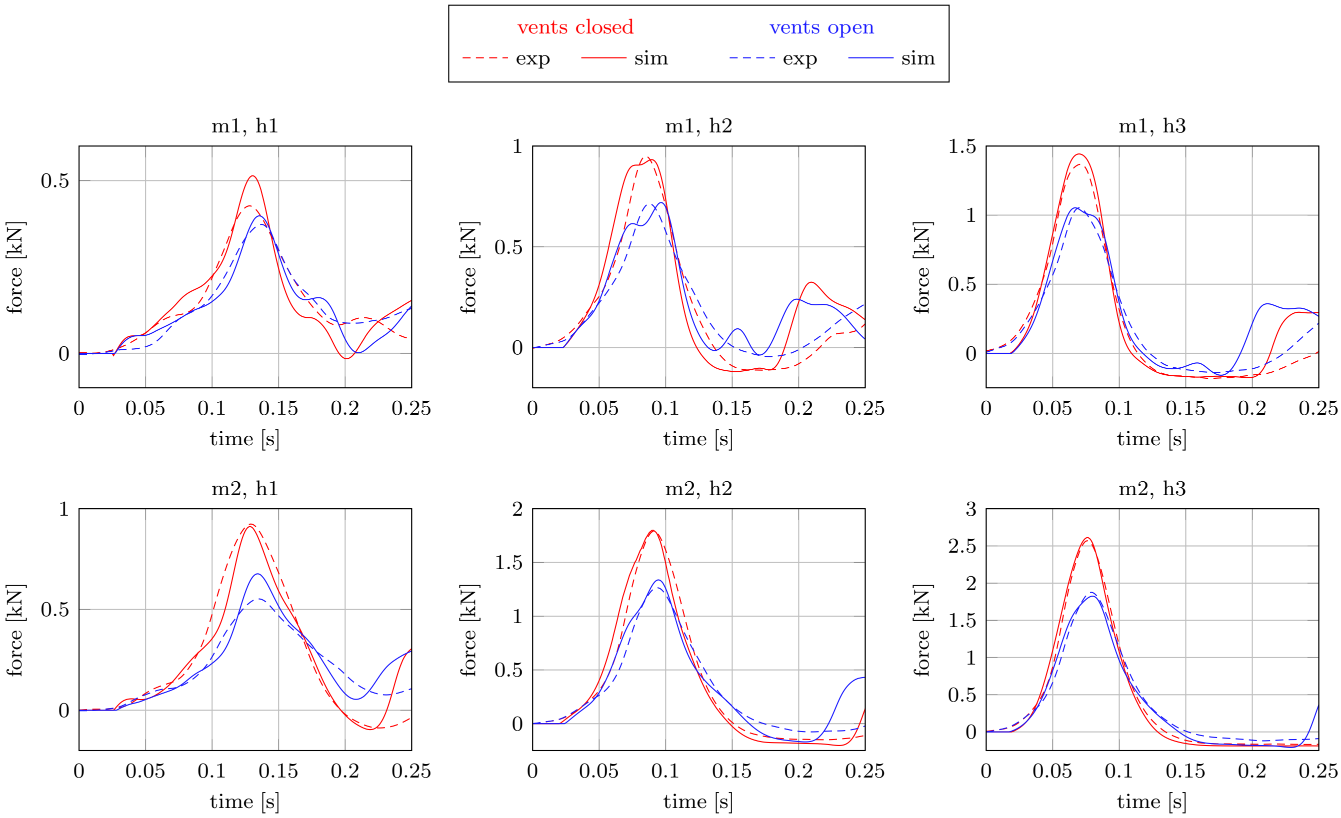

Fig. 10. Comparison of experimentally measured system response and simulated system response for sets of two different masses and three different drop heights

After ensuring that the elaborated FEM model was reliable, it was possible to run a series of simulations to obtain the optimal performance characteristics of the rescue cushion.

4. SYSTEM ADAPTATION UNDER UNCERTAINTIES

Validated model of the rescue cushion, presented in Sec. 3.2.2. was used in order to determine characteristics of the adaptive rescue cushion. In Fig. 11 maximum force as a function of impactor's mass and impact velocity was presented for two cases: passive airbag and adaptive airbag with vents opening optimized to both impact parameters. Both systems were excited with the same impact of plate-shape impactor of mass varying in the range of 5 and 25 kg. Impact velocities were varied between 5 and 15 m/s. Obtained reduction of maximum force achieved at least 15%, but there were cases where force was reduced for more than 60%, what means that the system response was mitigated more than twice. This very promising fact was a starting point for the analyses presented in Sec. 4.1–4.3.

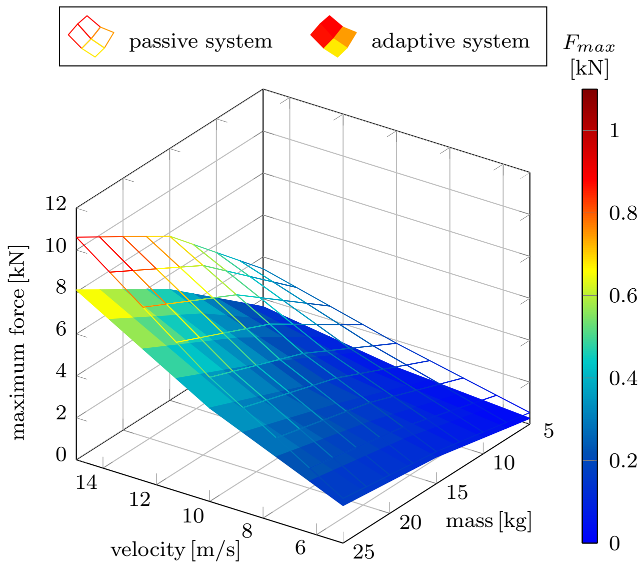

Fig. 11. Comparison of the maximum force characteristics of the adaptive rescue cushion (surface with filling) with the characteristics of the passive system (surface without filling)

4.1. *Adaptive performance under mass and velocity estimation inaccuracies*

The adaptation technique discussed in Sec. 2.2 results in transformation of the optimal valve opening surface into step graph. For the sake of clarity, the calculated adaptation areas of the vents' opening, which were used for further analyses, were shown in Fig. 12. Depending on the number of divisions applied to ranges of velocity and mass, different results were obtained. The denser division was applied, the closer to the optimal response was achieved. Nevertheless, minimal width of the obtained steps is limited by uncertainties included in the definition of adaptation areas, introduced in Sec. 2.2. The inaccuracy of velocity estimation was assumed at the level of 0.5 m/s and the mass estimation error at the level of 2.5 kg.

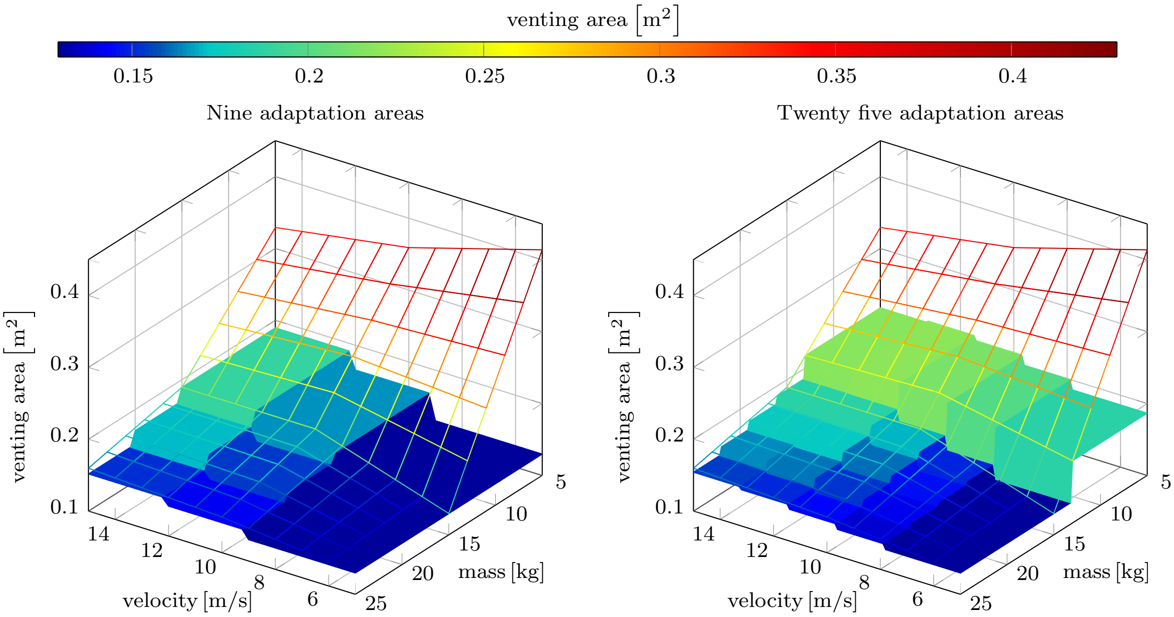

Fig. 12. Transformation of the optimal valve opening surface into step graph used for system adaptation under impact parameters' uncertainties

These values correspond to 5% and 12.5% of the parameter's range, respectively. The values for δ and ε are design parameters, which strongly depend on the applied impact identification method. The implemented approach will be the same for different values of these parameters. The efficiency of the proposed adaptation technique was evaluated by comparing the reduction of the maximum reaction force in two cases: one using the adaptation technique with the impact parameter range divided into 25 adaptation areas, and the other with optimal system adaptation, where there were no inaccuracies in impact parameters and no transformation of the adaptation surface into a reduced step graph. Relative reduction of maximum reaction force for the implemented adaptation scheme was shown in Fig. 13, which proved high performance of the proposed method. Despite a bit worse mitigation of the impact than in the optimal case, the obtained reductions of maximum force exceeded 15% and could reach up to 40%.

4.2. Optimization under impactor's shape estimation error

In addition to the mass and velocity values, the shape of the impactor also had a significant effect on the calculation of the vents opening area. In order to investigate this aspect, the system response was optimized using two rigid body impactors of spherical and plate-like shape. Comparison of the obtained areas of valves' opening determined for pairs of mass and velocity was shown in Fig. 14. For all considered conditions the difference of vents opening area was higher than 5%. It may exceed even 25% for selected impact conditions. In order to assess the influence of wrong assumption in terms of impactor's shape, two different impact conditions characterized by relatively high difference of obtained valves' opening were selected. In Fig. 15 force response of the system was compared for three cases: passive, optimally adaptive and adaptive with wrongly assumed shape of the impactor. The reduction of maximum reaction force comparing to ideal adaptive case was decreased by 30%. Nevertheless, when obtained results were referred to passive case, the system performance was much better. In order to assure safe operation of the rescue cushion it is recommended to calculate the valve opening using impactor of spherical shape, because it gave lower values of vents opening area. In the case the optimization of vents opening area was performed for the plate-shape impactor and then real conditions corresponded to spherical impactor, the dangerous contact of the impactor body with ground could appear because of too extensive gas release due to higher value of vents opening.

4.3. Influence of non-central impact

During the certification process the rescue cushion is evaluated also for performance under non-central impacts. Although, under such excitation the system is examined only in terms of stability, introduction of a novel functionality of the system adaptation requires taking into account the cases of different impact points. Within this study the extreme case where the impactor lands 25 cm from the side wall of the rescue cushion was analyzed. In Fig. 16 optimal vents opening areas calculated for central and non-central impacts were shown. Dark color palette was used in order to differentiate cases when contact with the ground was avoided, but the airbag ended up turned aside, from the cases of entirely proper system's operation, where both conditions of no contact with the ground as well as no fall over were met.

The difference in obtained values for majority of impact conditions was significant, what was clearly demonstrated by comparison of the force response for passive, optimal adaptive and adaptive system with impact conditions' estimation error. Inaccurate prediction of impact location may result in a worse than in passive case performance, what was shown in Fig. 17. It should be highlighted that graphs revealed the system re-

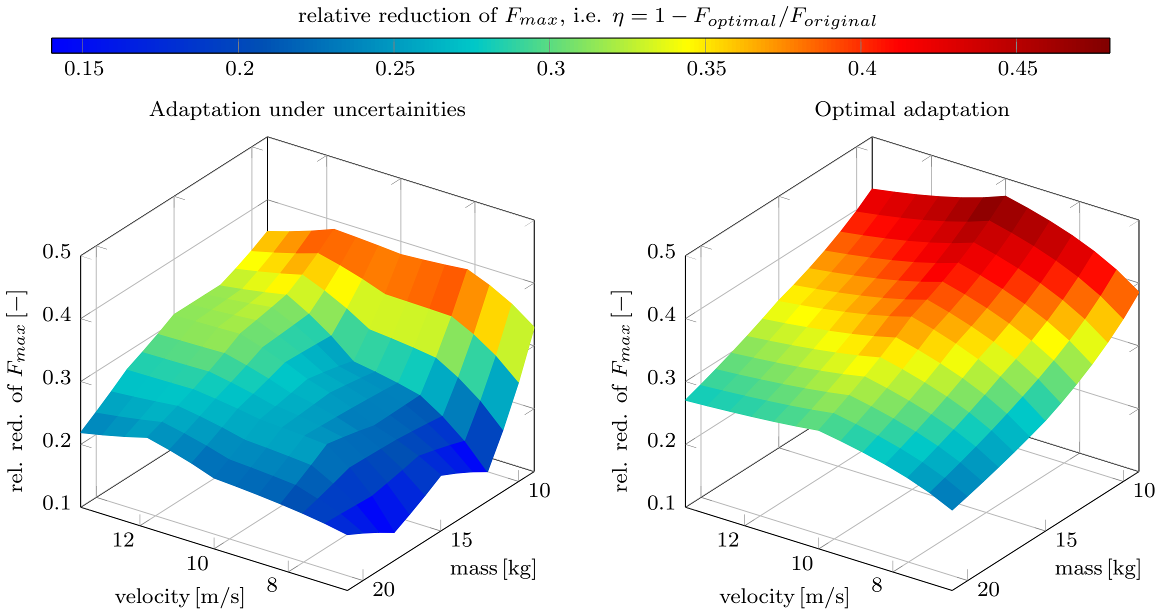

Fig. 13. Relative reduction of maximum reaction force as a function of impact velocity and mass in case of using proposed adaptation method and in ideal optimal adaptive case

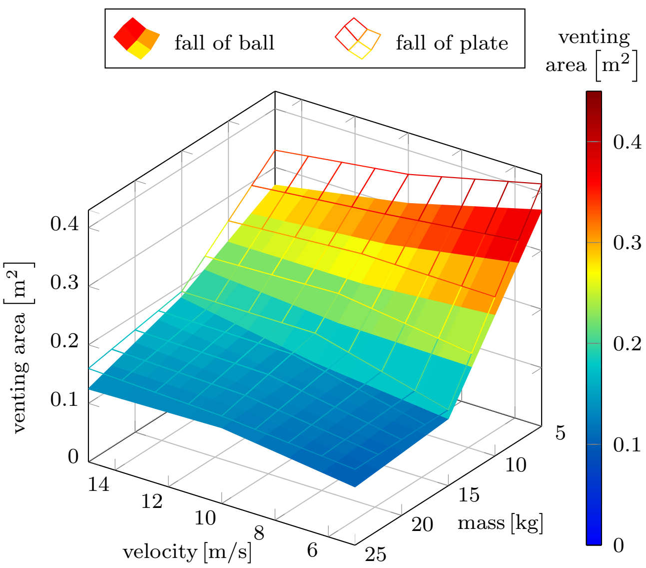

Fig. 14. Comparison of optimized vents opening as a function of impactor's mass and impact velocity for two different impactors: spherical shape (filled surface) and plate-shape (surface without filling)

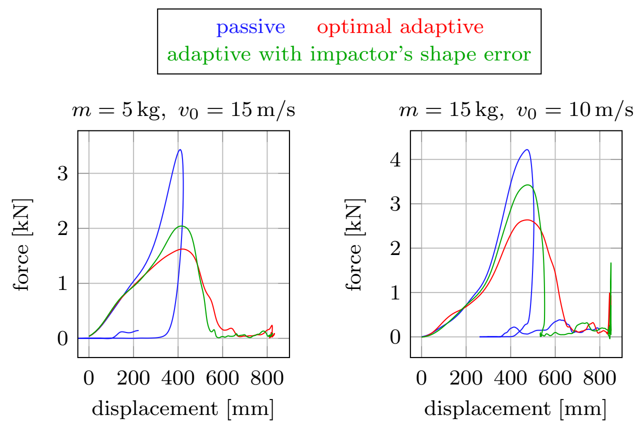

Fig. 15. Force response of rescue cushion in case of reference passive operation, optimal adaptive (adjustment of vents opening to actual impact conditions) and adaptive under error of predicted impactor's shape

sponse obtained for safer, lower value of vents opening. If calculation would be made for higher vents openings the system would fail and end up hitting the ground. For this reason, it was recommended to assume safer case with higher value of vents opening area or to consider further development of the rescue cushion by equipping it with impact parameters' identification system to estimate the impact position and optimize the system response properly.

5. CONCLUSIONS

Within this manuscript a novel type of a rescue cushion system, which is a pneumatic adaptive impact absorber for efficient protection of people falling from heights, was introduced and discussed in detail. The authors have introduced the reaction force minimization problem and utilized it to optimize rescue cushion's dynamic characteristics. This was done within the original adaptation approach, which was designed in a way corresponding to process uncertainties and operational requirements. The influence of dividing operational system conditions into different number of adaptation areas was analyzed. Possibility of errors in assumed shape of impacting body and non-central impact position was taken into account to evaluate sensitivity of the proposed method to unobvious parameters of the impact absorption process. Effectiveness of the proposed adaptation method was assessed using the FEM model validated with the experimental data obtained within a set of drop tests conducted on a laboratory-scale model of the rescue cushion.

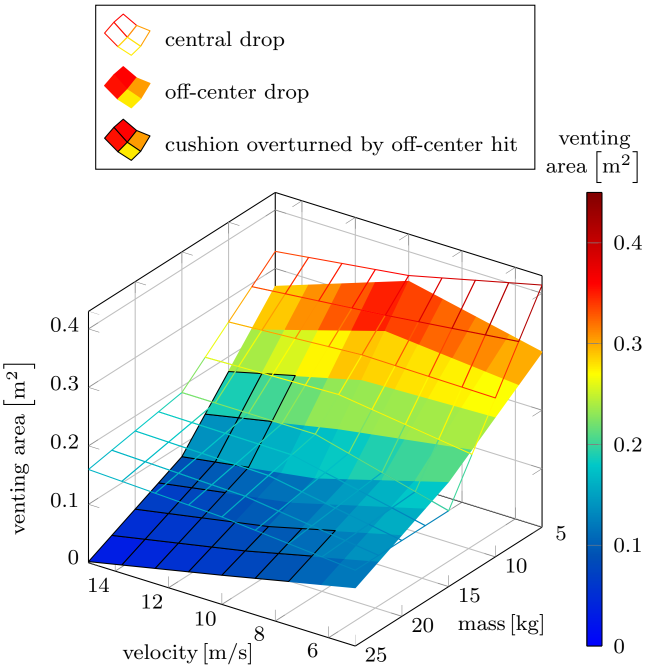

Fig. 16. Comparison of optimized vents opening as a function of impactor's mass and impact velocity for central impact (surface without filling) and side impact (filled surface); dark color palette applied for cases where impactor does not hit the ground but the rescue cushion is turned aside

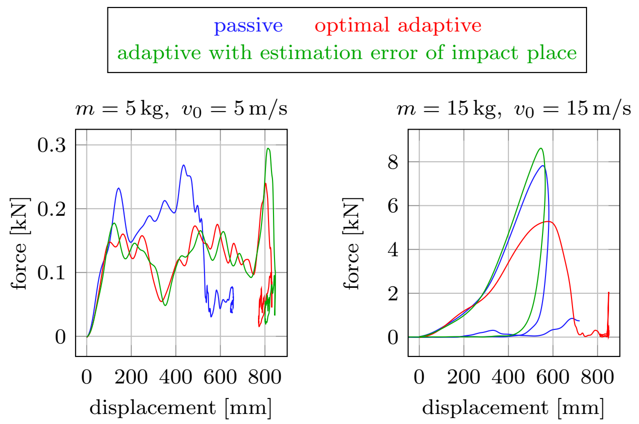

Fig. 17. Force response of rescue cushion in case of reference passive operation, optimal adaptive (adjustment of vents opening to actual impact conditions) and adaptive under wrongly estimated impact place

Except original analyses indicated within above paragraph, the significant contribution of the study is the fact that the energy absorbing capabilities of widely used passive rescue cushions can be significantly enhanced by implementation of the proposed, laboratory verified concept. It should be highlighted that the introduced system constitutes the first adaptive rescue cushion, since all devices revealed in the literature are purely passive. Comparison of the maximal forces acting on an object landing on the rescue cushion between passive and adaptive system shows that the latter provides much better results for majority of the considered impact conditions.

The further work of the authors will concern implementation of the discussed technical solution and the adaptation method on a full-scale rescue cushion system, as well as the development of an external identification module for system's adaptation to the estimated location of the impact.

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REFERENCES

[1] M. Tanvi Newaz, M. Ershadi, L. Carothers, M. Jefferies, and P. Davis, "A review and assessment of technologies for addressing the risk of falling from height on construction sites," *Safety Science*, vol. 147, p. 105618, 2022.

[2] O. Aneziris, I. Papazoglou, H. Baksteen, M. Mud, B. Ale, L. Bellamy, A. Hale, A. Bloemhoff, J. Post, and J. Oh, "Quantified risk assessment for fall from height," *Safety Science*, vol. 46, no. 2, pp. 198–220, 2008, occupational Accident Scenarios, and Accident Analysis Papers selected from the third international conference Working on Safety (WOS2006), September 12-15th, 2006, Zeewolde, The Netherland.

[3] M.-H. Noh and S.-Y. Lee, "Parametric impact performances in a new type crash cushion barrier system using an energy absorption pipe," *International Journal of Crashworthiness*, vol. 25, no. 1, pp. 106–119, 2020.

[4] J. Richert, D. Coutellier, C. Götz, and W. Eberle, "Advanced smart airbags: The solution for real-life safety?" *International Journal of Crashworthiness*, vol. 12, no. 2, pp. 159–171, 2007.

[5] Y. M. Goh and P. E. Love, "Adequacy of personal fall arrest energy absorbers in relation to heavy workers," *Safety Science*, vol. 48, no. 6, pp. 747–754, 2010.

[6] R. Faraj, B. Popławski, D. Gabryel, T. Kowalski, and K. Hinc, "Adaptive airbag system for increased evacuation safety," *Engineering Structures*, vol. 270, p. 114853, 2022.

[7] T. Tamura, T. Yoshimura, M. Sekine, M. Uchida, and O. Tanaka, "A wearable airbag to prevent fall injuries," *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 910–914, 2009.

[8] G. Mikułowski and R. Wiszowaty, "Pneumatic adaptive absorber: Mathematical modelling with experimental verification," *Mathematical Problems in Engineering*, vol. 2016, no. 1, p. 7074206, 2016.

[9] C. Graczykowski and R. Faraj, "Development of control systems for fluid-based adaptive impact absorbers," *Mechanical Systems and Signal Processing*, vol. 122, pp. 622–641, 2019.

[10] J. Zou, X. Guo, L. Xu, G. Tan, C. Zhang, and J. Zhang, "Design, modeling, and analysis of a novel hydraulic

energy-regenerative shock absorber for vehicle suspension," *Shock and Vibration*, vol. 2017, no. 1, p. 3186584, 2017.
[11] C. A. Martínez and O. Curadelli, "Testing and performance of a new friction damper for seismic vibration control," *Journal of Sound and Vibration*, vol. 399, pp. 60–74, 2017.
[12] D. Rodak, M. Żurawski, M. Gmitrzuk, and L. Starczewski, "Possibilities of vacuum packed particles application in blast mitigation seats in military armored vehicles," *Bulletin of the Polish Academy of Sciences Technical Sciences*, vol. 70, no. 1, p. e138238, 2022.
[13] P. Bartkowski, H. Bukowiecki, F. Gawiński, and R. Zalewski, "Adaptive crash energy absorber based on a granular jamming mechanism," *Bulletin of the Polish Academy of Sciences Technical Sciences*, vol. 70, no. 1, p. e139002, 2022.
[14] G. Mikułowski, R. Wiszowaty, and J. Holnicki-Szulc, "Characterization of a piezoelectric valve for an adaptive pneumatic shock absorber," *Smart Materials and Structures*, vol. 22, no. 12, p. 125011, Nov 2013.
[15] J. Holnicki-Szulc, C. Graczykowski, G. Mikulowski, A. Mróz, P. Pawlowski, and R. Wiszowaty, "Adaptive impact absorption – the concept and potential applications," *International Journal of Protective Structures*, vol. 6, no. 2, pp. 357–377, 2015.
[16] R. Faraj and C. Graczykowski, "Hybrid prediction control for self-adaptive fluid-based shock-absorbers," *Journal of Sound and Vibration*, vol. 449, pp. 427–446, 2019.
[17] C. Graczykowski and R. Faraj, "Extended identification-based predictive control for adaptive impact mitigation," *Bulletin of the Polish Academy of Sciences Technical Sciences*, vol. 71, no. 4, p. e145937, 2023.
[18] R. Faraj, C. Graczykowski, and J. Holnicki-Szulc, "Adaptable pneumatic shock absorber," *Journal of Vibration and Control*, vol. 25, no. 3, pp. 711–721, 2019.
[19] T. F. Browder, "Fire escape," US Patent 367 362, Aug. 2, 1887.
[20] T. F. Browder, "Life-saving machine," US Patent 952 871, Mar. 22, 1910.
[21] M. Pisarek, "Rescue devices – rescue cushions part 1; in Polish: »Sprzęt ratowniczy – skokochrony Część 1«," *W akcji*, no. 5, 2012.
[22] DIN 14151-2, "Rescue blankets and cushions - part 2: Jumping sheets type 8 - requirements, testing," Deutsches Institut für Normung, Standard, 2004.
[23] J. T. Scurlock, "Inflatable safety cushion system for controlled deceleration from falls of great height," US Patent 3 851 730, Dec. 3, 1974.
[24] P. Lorsbach, "Safe escape mattress," EPO Patent 0 200 998, Nov. 12, 1986.
[25] DIN 14151-3, "Rescue cushions – part 3: Jumping cushion type 16 – requirements, testing," Deutsches Institut für Normung, Standard, 2016.
[26] M. Vetter, "Pneumatic jump rescue device," DE Patent 100 29 193 B4, Oct. 04, 2007.
[27] P. Geuenich and W. Schnicke, "Pneumatic emergency apparatus having hose frame and tarpaulin," WO Patent 2020/089266, Oct. 30, 2019.
[28] U. Kann and H. Koelsch, "Safety device for pressurised bottles," EPO Patent 2330335, Jun. 08, 2011.
[29] R. Faraj, T. Kowalski, D. Gabryel, B. Popławski, and J. Całka, "Polish patent application submitted to Patent Office of the Republic of Poland, no. 441588, »System of adaptive release valves for an airbag, in particular the rescue cushion, and the airbag including the system«, title in Polish: »Układ adaptacyjnych zaworów upustowych poduszki powietrznej, w szczególności skokochronu, oraz zawierająca go poduszka powietrzna«," 2022.
[30] Human Biomechanics and Simulations Standards Committee, *Human Tolerance to Impact Conditions as Related to Motor Vehicle Design*, Feb 2011.
[31] Versace, John, "A review of the severity index," in *15th Stapp Car Crash Conference (1971)*. SAE International, feb 1971.
[32] F. Bandak, R. Eppinger, M. Haffner, N. Khaewpong, S. Kuppa, M. Maltese, T. Nguyen, R. Saul, E. Sun, E. Takhounts, R. Tannous, and A. Zhang, "Development of improved injury criteria for the assessment of advanced automotive restraint systems : II," The National Highway Traffic Safety Administration, Tech. Rep., Nov 1999. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/14738
[33] H.-W. Henn, "Crash Tests and the Head Injury Criterion," *Teaching Mathematics and its Applications: An International Journal of the IMA*, vol. 17, no. 4, pp. 162–170, 12 1998.