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Numerical and Experimental Assessment of the Performance of Wearable Airbags for Motorcycle Riders

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***Abstract*—Wearable airbags are relatively recent for the motorcycle-garments industry, and their development still relies mainly on trial and error through experimental testing. The application of numerical simulation is still in its infancy. The present work aims at assessing the performance of wearable airbags for motorcycle riders. The model of an existing airbag is built and simulated on two typical test scenarios. The results are compared to the corresponding experimental findings. The first scenario is derived from the drop test used for certifications according to EN 1621. The results are used to calibrate the virtual model and to estimate the bag material properties by comparison of numerical and simulated anvil peak force. In the second scenario the airbag model is fitted on a Hybrid III 50th dummy model and validated in a thorax impact test, according to 49 CFR 572. Such test has been performed and simulated both with airbag and without airbag to assess the airbag contribution – the focus is on the dummy's chest deflection. Finally, 49 CFR 572 along with its low-speed variant (SAE J2779) are simulated to perform a parametric analysis on the effect of inflation pressure and inflated thickness on the airbag performance.**

***Index Terms*—wearable airbag, drop test, thorax impact test, motorcycle safety, simulation**

I. Introduction

AIRBAG systems first appeared in production cars in the US in the 1970s and are now a standard equipment in most cars [1], [2], [3]. Numerical simulation is a customary tool when it comes to the development of airbags for the car industry, see e.g. [4], [5].

Airbag systems have appeared only very recently on production motorcycles. The first one appeared in 2006 on the Honda Gold Wing, with the aim of mitigating the consequences of frontal collisions. Some of the experimental investigations related to such airbag were published in the late 1990s [6], [7], while numerical simulations were later reported [8]. More recently a new concept of airbag mounted on a motorcycle has been presented [9], [10]. This system differs from the former because the airbag does not need a support system or reaction structure in place during deployment. The possible application of frontal airbag to smaller motorcycles has been discussed in [11], [12]. Research on airbags mounted on motorcycles were also reported by Yamaha [13]: both sled and full scale tests with related simulation were reported - in this case the airbag was installed on the front-end of the rider's seat and supported by a back-plate. Finally in [14], a frontal airbag system is tested and simulated on a three-wheeled vehicle, again the focus is on frontal collision.

Wearable airbags are another option when it comes to the protection of motorcycle riders. One of the advantages is the possibility of protecting riders in low-side and high-side crashes [15], [16] and oblique collision, where frontal airbags mounted on the motorcycle would clearly be not effective. There are two main activation systems in the case of wearable airbags: mechanical (a wire between the bike and the rider is pulled when the rider falls) and electronic (accelerometers and/or gyrometers on the bike and/or on the rider detect the fall and trigger the airbag activation). Among the advantages of mechanical activation are simplicity and robustness when it comes to activation (when the wire is pulled the system triggers the airbag, while an electronic system relies on a fall detection algorithm that could fail the detection of some falls). Among the disadvantages are the possible interference between the rider and the activation wire and the need for the rider to fall 'enough' to pull the wire and trigger the activation. A number of systems of this kind have been available on the market since the late 1990s, e.g. [17], [18], [19], [20], [21]. On the other side there are systems based on electronic activation, i.e. on algorithms that detect the fall using some 'function' computed from the sensors output, see e.g. [22], [23]. The first airbag of this kind was made available by Dainese in 2007 for race riders [24] and in 2011 as a commercial product [25]. As of today, there are only few other race [26], [27] and road [28], [29] products of this kind. From 2018 airbags fitted on race rider's suits are compulsory within the FIM MotoGP World Championship.

Most of the development of wearable airbags for motorcycle rider suits has been experimental. The present work aims at simulating the performance of a wearable airbag system for motorcycle riders using numerical simulation through the code Madymo. Two scenarios are considered: the drop test and the thorax impact test. The former is used to estimate bag material properties, while the second is used to assess the performance of the airbag system. Finally, a parametric investigation on the main airbag characteristics is carried out. The simulations and tests have been performed using the Hybrid III 50th dummy model. In this study the pressure within the airbag volume is assumed constant (although time-varying) – this is a good assumption in the case the inflation process is not the main focus of the analysis – and the airbag is assumed perfectly inflated at the instant of impact.

The work is organized as follows. In section II the drop test for the identification of the main airbag parameters is

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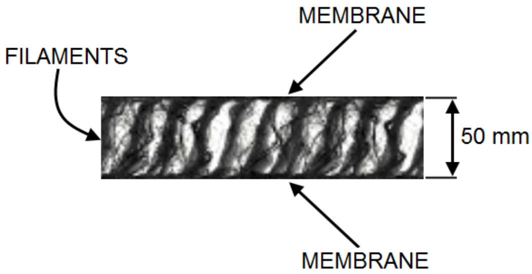

Fig. 1: Airbag membrane and filaments, section view.

described. In section III the thorax tests, with and without airbag, are presented and compared against experimental findings for the validation of the numerical model. Finally, in section IV a parametric analysis on the main airbag parameters is carried out using both low-speed and high-speed thorax tests. Some of the results presented are normalized for confidentiality reasons.

II. Drop test

The drop test is considered in EN 1621, namely Part 4 (Motorcyclists' inflatable protectors – Requirements and test methods), for the certification of mechanically activated airbag systems. However, certification bodies often make use of the same requirements also for electronically activated systems [30]. In the test, a striker falls on the protector, which is on top of an anvil attached to a force transducer. The main outcome of the test is the peak force transmitted to the anvil, which determines the certified level of protection.

The airbag considered in this research is made up of two membranes stitched on the edges. Each membrane consists of a thermoplastic material and a fabric material, plus internal filaments of the fabric material, see Figure 1, that are in tension when the airbag is inflated. When the airbag is inflated, some of these inner filaments are slightly inclined and thus contribute to the planar stiffness of the membrane. Because of the complexity of the material employed, simple tests on the sole membrane element proved not suitable to obtain the mechanical characteristics of the airbag (e.g. missed stiffening effect). It was then decided to perform a number of drop tests on the airbag at the nominal inflation pressure, both numerically and experimentally, in order to identify the main material properties. The virtual model of the experimental set-up is shown in Figure 2, and consists of a 0.6×0.6 m bag. Both impactor and anvil were hemispherical, 0.1 m in diameter: this geometry, without sharp edges, does not damage the bag material, thus allowing multiple tests. Due to the geometry of the bag, reduced impact energy values have been chosen, in order to avoid direct impact between impactor and anvil.

The bag is discretized using membrane elements, whose maximum size is 20 mm (reduction of the size down to 5 mm did not show significant variations in the results), while the filaments are modelled through spring-damper elements. For simplicity, the material model selected for this study is linear-isotropic, i.e.

$$\sigma = S\varepsilon + \gamma\dot{\varepsilon}, \tag{1}$$

where σ is the stress vector, ε the strain vector, $\dot{\varepsilon}$ the strain rate vector, S is the well known stiffness matrix for linear-isotropic materials (which depends on the Young modulus and Poisson ratio only), and γ is a rate sensitivity parameter. The latter is defined as

$$\gamma = Ed\Delta t_e, \tag{2}$$

where E is the Young modulus, d is a damping factor and Δt_e is the element time step, i.e. the time required for a sound wave to cross the element – undamped Courant time step. The integration time step Δt employed is the minimum of all Δt_e, scaled down by the factor $(\sqrt{d^2+1} - d)$ to account for the effect of damping that reduces the maximum step size allowed for stability [31]. In this study the damping factor is $d = 0.2$ (after simulation over a wide range of values showed negligible effects) and the Poisson ratio is zero (again after simulations over a wide range of values). The parameters for the filaments are their stiffness k and damping coefficient c – both assumed constant

$$F = k\Delta l + c\dot{\Delta l}, \tag{3}$$

where F is the force resulting from deflection Δl and deflection rate $\dot{\Delta l}$. Actually, the meaningful parameter for the filaments is the stiffness per unit area: from this value, the stiffness of the single filament is obtained.

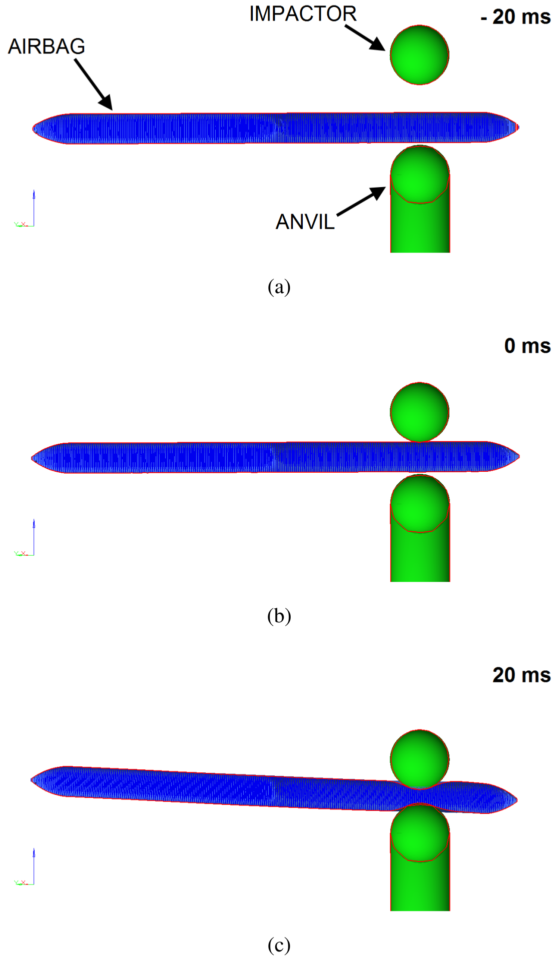

Fig. 2: Drop test simulation: (a) before the impact, (b) at impact and (c) at maximum airbag compression.

Different drop tests have been simulated and compared to the experimental findings in order to obtain such parameters. The values of the damping coefficients, for both

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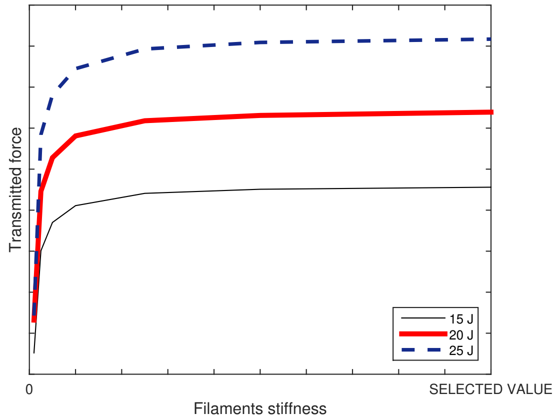

Fig. 3: Effect of filament stiffness on the peak of the transmitted force.

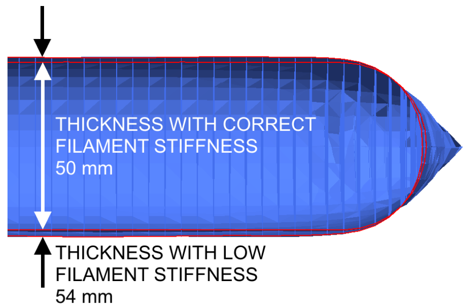

Fig. 4: Difference in inflated airbag geometry caused by different filament stiffness.

the membrane elements and the inner filaments, proved not significant: the peak and shape of the anvil force is minimally affected by the damping. The stiffness of the inner filaments affects the transmitted force only at very low values and then quickly saturates over a certain threshold, see Figure 3. This is because, for a given inflation pressure, low stiffness filaments deform significantly, allowing a higher distance between the two membranes and thus changing the reference geometry of the airbag; see Figure 4. This behaviour was not observed on the real airbag, which maintains a constant thickness in a wide range of inflation pressure. For this reasons, the filaments' linear stiffness was chosen in the saturation range, in which the height of the airbag and the transmitted force remains constant.

The last parameter that needs to be determined is the Young modulus of the membrane elements. The results of the analysis are reported in Figure 5. This was found to be the parameter with the largest influence on the force transmitted to the anvil in the drop test. In order to find a suitable value for modelling the behaviour of the real airbag in an impact, the Young modulus was determined by matching the peak of the transmitted force calculated in the simulations with that obtained in the experimental test.

Summarizing, at the end of the drop test campaign the elastic modulus of the membrane, the stiffness of the filaments and the damping coefficients of the airbag are available.

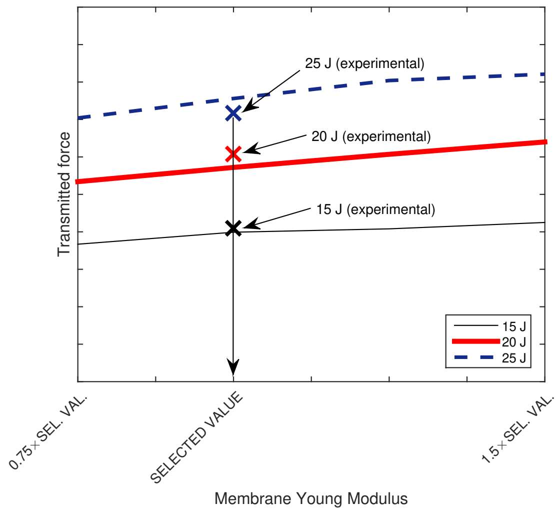

Fig. 5: Effect of membrane Young modulus on the peak of the transmitted force. Cross markers represent the experimental values for each energy level.

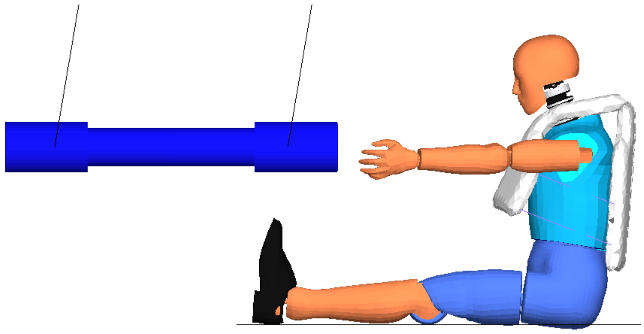

Fig. 6: Thorax impact test virtual model.

III. Thorax Impact Test

The thorax impact test is considered in 49 CFR 572, for the certification and calibration of dummies. This test is considered especially relevant for the assessment of the performance of thorax protectors such as wearable airbags. The simulated test reproduced the corresponding experimental test previously carried out. A 0.1524 m diameter cylindrical pendulum of mass 23.36 kg hits the chest of an instrumented dummy at a velocity of 6.7 m/s. The dummy is placed on a flat, smooth, horizontal steel surface and can thus slide during the impact. In order to pass the test, the measured chest deflection has to lay in the interval 0.0635-0.0726 m. This test configuration (see Figure 6) was chosen as the most meaningful and reproducible to verify the performance of a new chest protector during the APROSYS project [32]. As the chest is one of the areas covered by most wearable airbags intended for road use, this test method was also identified as one of the tool to assess the performance of inflatable protectors on this part of the body.

Preliminary steps for the simulation of the thorax impact test involve the modelling, meshing and fitting of the virtual airbag to the dummy model. The selected dummy is a Hybrid III 50th Percentile, which is the same used in the full scale experimental test. The airbag was first modelled as a flat 'shell' element. Then its shape was adapted to the body of

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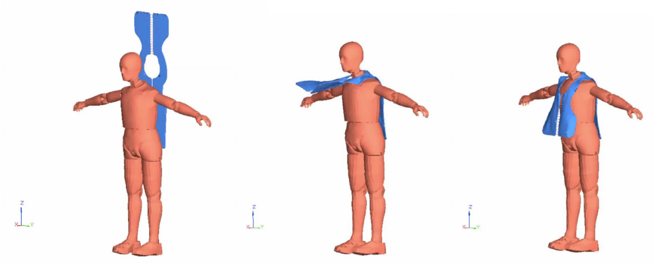
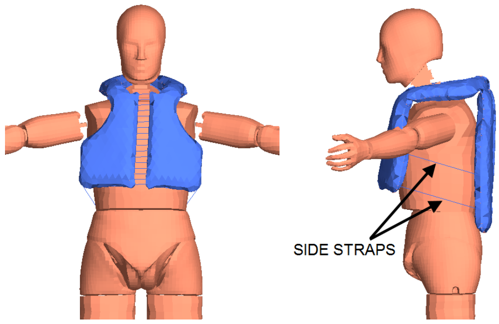


Fig. 7: Fitting process based on accelerations fields to obtain the initial shape of the airbag finite element model – the final step before simulation will involve the addition of the side straps and back connections shown in Fig. 8.

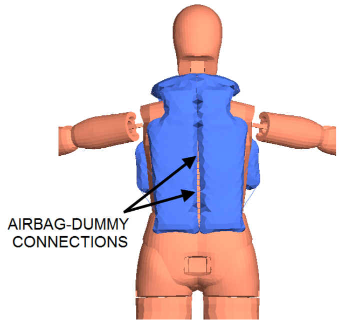
the dummy through the application of acceleration fields to the finite elements that make up the airbag numerical model. This process is repeated in multiple steps, as depicted in Figure 7, each time adapting direction and intensity of the acceleration fields applied, until a satisfactory shape of the airbag is obtained. Alternative techniques can also be adopted, depending on the shape of the airbag and the body areas it has to cover.

In the next step, the airbag needs to be linked to the dummy in order to prevent its motion when inflated and ensure it is hit by the impactor during the test. In the real system this is achieved accommodating the bag inside a technical jacket or integrating the bag in a vest worn over the jacket. In the virtual model, it is important that the connection fulfils its function of keeping the airbag in the right position, but at the same time it should not alter the interaction between dummy and airbag. To attain such result, two couples of symmetrical nodes (one on each of the two chambers) on the rear part of the airbag were connected to two point on the back of the dummy through visco-elastic constraints. Furthermore, four additional one-dimensional elements ('side straps') were added to the finite element model to link the front and rear parts of the airbag. This is necessary because, as the internal pressure increases during the inflation process, the airbag tends to straighten up, losing its correct shape. The resulting shape of the inflated airbag model in shown in Figure 8, where the side straps are clearly visible.

At this point, the model can be simulated. Among the many outputs that can be monitored, the focus is on the chest deflection, which is also used for the certification of dummies. The standard test, which does not include the airbag, gives a chest deflection signal very close to that obtained in the experimental test, with a slightly lower peak value (-3%) in the simulation, see Figure 9a. This result confirms that the numerical model of the dummy and the experimental set-up have been built correctly. The simulation with the airbag fitted to the dummy shows again a chest deflection signal qualitatively similar to the experimental one, this time with a larger peak value (+7%) in the simulation when compared to the actual test, see Figure 9b. In other words, the virtual airbag proves a little less protective than the real device, reducing the peak chest deflection by 18% instead of 26%. The differences found between simulation and real tests are reasonably small and can be considered satisfactory – in addition the simulation results are conservative. At this stage,



(a) (b)



(c)

Fig. 8: Airbag finite element model fitted to the Hybrid III 50th dummy: (a) front view; (b) side view (the side straps are highlighted); (c) rear view (the connections between airbag and dummy are highlighted).

the virtual airbag model is considered validated.

IV. Parametric Analysis

The effect of the main parameters on the airbag response has been investigated using the virtual model validated in the previous section. Two characteristics, potentially alterable also in the real product, have been considered: the inflation pressure, which is varied by changing the total mass of gas used to inflate the bag, and the thickness of the inflated bag, that can be adjusted by changing the length of the inner filaments. Moreover, in addition to the standard thorax impact test, its low-speed variant SAE J2779 ('Low Speed Thorax Impact Test Procedure for the HIII 50th Male Dummy') was simulated. The same set-up used in 49 CFR 572 is employed, but the impactor speed is reduced to 3 m/s. This low-speed test was created to satisfy the demand for a calibration test where the energy involved is comparable to an actual low energy automotive impact test.

Figures 10a and 10b report the effect of the inflation pressure and airbag thickness on the peak chest deflection, for the low-speed and the high-speed tests respectively. With the aim of minimizing the peak chest deflection, an optimal value of inflation pressure can be found for given impactor speed and airbag inflated thickness. The following physical interpretation can explain the existence of such optimal value. For pressures below the optimal one, the impactor fully compresses the airbag and hits the dummy's chest. In this range, an increase in the airbag pressure reduces the impactor deceleration and its relative velocity when it impacts the chest. On the other hand, above the optimal value, an increase

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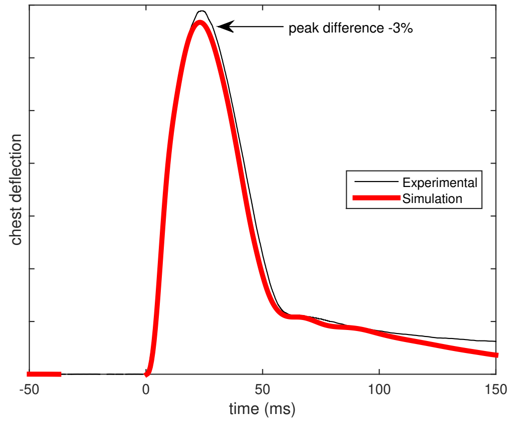
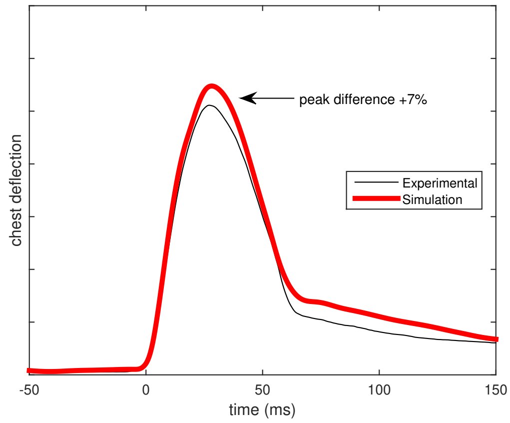
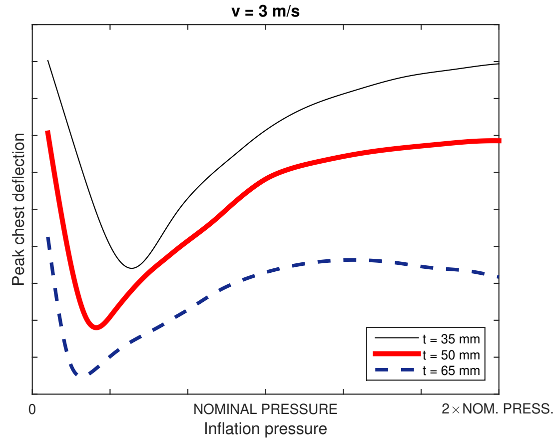


(a)

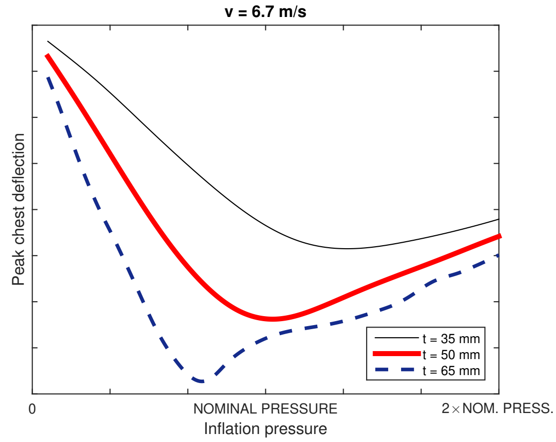


(b)

Fig. 9: Chest deflection as a function of time: a) without airbag; b) with airbag.



(a)



(b)

Fig. 10: Effect of airbag inflated thickness and inflation pressure on peak chest deflection: a) low-speed thorax impact test; b) high-speed thorax impact test.

in the airbag pressure reduces the airbag compression when it is hit by the impactor, and thus the impactor deceleration is more rapid, resulting in a higher peak chest deflection. At high pressures the response becomes almost constant, with a chest deflection lower than that obtained without airbag, since the load is distributed over a larger area. Ultimately, the optimal pressure that minimizes the peak chest deflection is the lowest value sufficient to prevent the impactor from hitting the chest, after full compression of the airbag. In the low speed scenario, the variation in the peak chest deflection between the optimal pressure and the high pressure (when saturation occurs) is around 17% in the case of 65 mm thickness and 26% in the case of 35 mm thickness. In the high speed scenario, the difference is 12% and 6% for 65 mm and 35 mm respectively. Therefore the low speed condition with the low thickness airbag is the scenario most sensitive to pressure optimisation.

Analysing the effect of the other parameters, it can be observed that the higher the airbag inflated thickness, the lower the optimal pressure for a given impactor velocity. In addition, lower peak chest deflection values correspond to higher inflated thickness values at each pressure: this means that, regardless the pressure, choosing the highest thickness allowed by the ergonomic constraints is always advantageous.

It can also be noticed that, as intuition would suggest, higher impact energies (i.e. higher impactor velocities) require a higher inflation pressure to minimize the peak chest deflection, given the inflated thickness of the airbag.

V. Conclusions

A wearable airbag system aimed at the protection of motorcycle riders has been studied. The virtual model has been calibrated using a drop test and then used on a thorax impact test to assess the protection performance of the airbag, in terms of chest deflection of a Hybrid III 50th dummy model. A good agreement has been found between the numerical tests and the experimental tests. The validated model has then be used to investigate the effect of inflation pressure and airbag inflated thickness finding that, for each thickness, an optimal pressure that minimizes chest deflection exists.

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