Design and numerical evaluation of an airbag-jacket for motorcyclists

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Abstract

The need of passive safety devices, able to reduce the accidents and the severity of injuries suffered by motorcyclist, distinctly arises from data on accident statistics.
In this paper, the effectiveness of an airbag device fitted in the biker's garments has been verified through various numerical simulations. Two simple test conditions were defined, in order to investigate the performance of the device both for back and front impacts, and simulated at various impact speeds. With the aim of providing more information about the actual capability of the airbag to reduce the severity of the injuries, one of accident scenario described by ISO 13232:2005 has been also investigated, checking the real effectiveness of the airbag strap-based firing system too.
Confrontation of injury indexes resulting from simulation with and without airbag made possible a realistic evaluation of the harm reduction induced by the airbag presence.

INTRODUCTION

Accidents involving two wheelers are assuming a significant social cost [1], and their dynamics is really more complex and diversified than accidents involving only cars and their occupants [2] since the kinematics of biker's body can be influenced by a wide range of variables. So, motorcycle airbags must be compliant with far more specifications than an automotive one and need a more careful and accurate design. Often also a totally different design approach is required. There are two different kinds of airbag for motorcyclists, mounted on the vehicle [2, 3, 4] or fitted in biker's garments [5, 6].
The inflation of the devices mounted on the motorbike is activated by one or more accelerometers put on the vehicle body or even on the wheel mount [2, 3], to get earlier information when a frontal impact occurs. The bag itself is generally quite big (150 liters) and, to obtain acceptable inflation times, a pyrotechnic inflator is used. These characteristic leads to devices with very short reaction times and a fast inflation, but only if the motorcycle is involved in a frontal impact against another vehicle. The greater limit of these devices is that they work properly only under particular conditions. Especially, the biker must remain on the motorbike during the accident and the impact dynamics must lead him to hit exactly the part of his vehicle protected by the airbag.
Airbag devices intended to be fitted into motorcycling equipment are smaller than motorcycle mounted ones: generally the capacity of these devices ranges around 20-40 liters. Inflation is achieved via compressed gas stored in a cylinder and can be triggered by electronic instruments [6] or by a mechanic wire. The electronic instruments are accelerometers, as for the bike mounted devices, gyroscopes and proximity sensors, that can be installed both on the vehicle and on the rider's suit. The other kind of activation system, is a wire, or a strap, joined to the motorcycle at one extremity and to the airbag at the opposite one; when tensile force on the wire rises above a prescribed value, the inflator is activated and at the same time the link between wire and suit breaks, freeing the rider from his bike. The simplicity and reliability of this last activation method make it the most diffused amongst commercial devices. Generally, airbag fitted in garment, show slower reaction times than airbag mounted on the vehicle, whichever is the activation method. The rider, and the instruments fitted in his garments, "detects" the impact slightly later than the frame or the front wheel of the bike, while the wire needs the biker to move away from his riding position to get tensed and trigger the activation. The shape of these airbags can be very various, according to the chamber capacity and the body areas the device is intended to protect, which generally are neck, shoulders and lumbar spine. Following the biker during all the duration of the accident, an airbag fitted in garments can protect against a wider range of injuries.
The performance of an airbag is influenced by many factors, amongst them the most effective are the impact energy, the area of impact, the airbag inflation pressure, the chamber volume and shape and the presence of holes on its surface. The impact energy depends uniquely on accident dynamics, while the impact area also depends on airbag shape: in real accidents these parameters are really unknown. During the design and optimization process of an airbag, these values should be supposed considering various accident scenarios, and the device will be optimized according to these suppositions. The volume and the pressure of the chamber depend on airbag typology, inflator type and design goals. Usually, the best match between

performance and feasibility (weight, fitting in clothes, look, and so on) is researched; for airbags intended to be worn by the rider, wearing comfort is also important and must be considered, to avoid highly effective device that are uncomfortable and hamper a safe riding. Finally, the presence of holes in an airbag can greatly change the behavior of the airbag itself, though the holes introduce dissipative effects due to the outflow of air, leading to a possible reduction of transmitted forces. Larger holes bring a greater energy dissipation, but also a quicker reduction of the gas mass in the airbag chamber; so, high section holes need an airbag with adequate volume and pressure to grant a good injury reduction.

In this paper are reported the numerical simulations performed on a wire-triggered airbag device, fitted in a jacket, in order to estimate its performance during an accident. Two ad hoc scenarios were assembled to accurately investigate the device behavior in two different, and quite opposed, kind of impact. These simple scenarios were chosen to reduce the number of factors involved and underline the main characteristics of the airbag. After these analysis, the behavior of the airbag has been investigated also in a more realistic accident scenario, proposed by ISO 13232:2005 [7] and involving a motorcycle impacting on a standing car side with a 90° angle.

Performed studies contributed in design and set up of jackets, both for men and women, with an high fashion feature and easy to wear, embodying an airbag device. These "Life Jacket", branded by Brembo Spa, were presented in May 2010 and will be delivered on the market since Fall 2010.

EFFECTIVENESS EVALUATION OF SAFETY DEVICES

A very delicate matter, in accident research and evaluation of safety devices, is to find a correlation between measurable solicitations, as forces, accelerations or displacements, and real biological injuries. In this task, there are two main difficulties to get round; the first one is the great variety of the human genus, that means that different people can stand very different levels of solicitation before taking damage. Also restricting studies to a very specific group, as adult males with mass and height of 50th percentile, without any particular pathologies, leads to highly scattered results, so, any conclusion drawn can be only statistical.

The other problem to get round is collecting reliable data to fix the threshold values. Obviously, impact test with live people can't be performed, excepting for test with carefully low solicitations, no over the pain level, conducted on volunteers. Some other data are collected via experimentations on cadavers, but in many countries the legislation puts strict limits on these activities. So, most studies on accidents and safety devices are performed on Anthropometric Testing Devices (ATDs). ATDs are very sophisticated instrumented dummies, designed and validated to reproduce as accurately as possible the behaviour of a human body as concerns dimensions, mass and their distribution, kinematics and dynamics of the articulations, deformation under loads and so on. For numerical studies, to get results that are comparable with experimental data, virtual models of these dummies are employed; these models try to reproduce the behaviour of real ATDs, in the same way real dummies try to reproduce real body behaviour.

Of course, during the design and validation process of a dummy or its numerical representation, the most efforts are put on those movements and solicitations of interest for the kind of accident they are intended to study. So, biofidelity of dummies, both real and numerical ones, is no constant through all the possible impacts, and this must be considered when processing data and assessing whether an accident is potentially dangerous for a real man or not.

Hybrid III family dummies were developed by GM since 1976. They are designed to research the effects of frontal impacts, and are less valuable in assessing the effects of other sorts of impacts, such as side impacts or rear impacts. Nevertheless, they still are the most versatile and reliable dummies, also thanks to the great mass of data about it available. In fact, Hybrid III employment is prescribed also in homologation tests on biker protecting devices fit on road restrains systems (UNE 135900:2008 [8]). The MATD (Motorcycle ATD) is a modified Hybrid III dummy, whose specifications are defined in ISO 13232:2005, with frangible limbs and the possibility to accommodate the neck in positions that are more likely to those assumed by a motorcyclist [9]. Modifications adduced on MATD have been estimated as non significant for test purposes and a numerical model of an Hybrid III 50th percentile male dummy has been employed in this study.

In the tests described in this paper, dummies are subjected to impacts and solicitations that may be considerably different from those whose is subjected a car occupant during a frontal accident, so, for each kind of test and each part of the body examined, the most appropriate injury indexes have been considered.

Head Injury Criterion (HIC) was used in all the simulations performed. HIC is a quite universally accepted injury index, adopted by both U.S.A. and European safety normative. This criteria estimates head damage by the maximum integral achievable on a fixed length time interval of head acceleration.

All normally used injury indexes about neck damage are referred to different situations than those simulated during this work. Using an injury index for a situation that's not whose for which it has been formulated and validated is really unadvisable, so in this paper the maximum force and torque acting on the neck load cell are directly reported. Because of the abovementioned biofidelity limits of the Hybrid III dummy, only x-direction force and y-direction torque have been considered. The x-axis of the load cell lies on the symmetry plane of the dummy, proceeding frontwards from the dummy. The y-axis instead is perpendicular to the symmetry plane directed leftwards, so a positive torque means neck flexion, with the chin moving towards the chest and a negative torque means neck extension, with the chin moving away from the chest. To get a reference and state whether a solicitation is potentially harmful or not, simulation data were confronted with threshold values proposed by UNE 135900:2008 [10].

For frontal impacts, the Combined Thoracic Index (CTI) is a widely adopted injury index. It takes into account both maximum acceleration and maximum deflection suffered by the thorax of the dummy. In case of rear impacts, CTI is not a reliable index as the chest deflection is measured frontally, so for the simulation of rear falls, thorax and pelvis acceleration have been acquired and considered, instead of CTI.

MODEL BUILDING

The airbag

The airbag consists in a tubular air chamber (Figure 1) fitted in an ordinary jacket; the section of the chamber is variable in order to convey a greater gas volume to protect the most vulnerable body parts. The volume of the chamber is quite smaller than most of airbag actually available on the market (about 15 liters instead capacity that ranges around 20-40 liters), in order to achieve significantly faster inflation times and improve dressing comfort and easiness of use. The device presents the most part of the volume disposed around the neck and along the lumbar spine thus these are the principal body parts it's intended to protect. A strap (Figure 2), connects an inertia reel, firmly joined to the motorcycle chassis, with the percussion pin of a cylinder, filled with CO_2. When the strap is pulled over a certain activation force, it disengages from the percussion pin, allowing gas to expand into the chamber and inflating the airbag. The device is characterized by shorter inflation times than others, and after 70 ms from the firing it already reaches about half its nominal pressure, that's enough to have a significant effect during an accident.

The geometry of the device has been rebuilt in CAD environment, thanks to measures detected on a physical prototype of the airbag and the original paper patterns used to cut the tissue to envelop the air chamber. From this geometry, a mesh has been created, obtaining a Finite Element model of the airbag. To simplify the model, and reduce calculus times, only the gas chamber and the straps that keep the jacket frontally fastened was modeled.

Figure 1. Airbag chamber

Figure 2. Activation strap

Figure 3. End of dressing phase: dummy sitting on the motorcycle and wearing the airbag

Dressing

Some operations were performed on the FE model of the airbag, in order to obtain a good dressing on the airbag itself over the dummy's body (Figure 3). As a first step, the airbag model has been folded, to bring it to a shape that is nearer to its real condition when it's worn by the biker. Moreover, the airbag has been introduced in MADYMO environment and two subsequent simulation were performed, with the airbag subjected to gravity and stiffness of the straps, coming to a very realistic positioning over the chest of the dummy. In the first simulation the arm of the dummy are wide apart, to avoid interferences between arms and airbag, in the second one the dummy is exactly in the same position it assumes on the bike.

Inflation

The carbon dioxide (CO_2) is stored in the cylinder at ambient temperature and very high pressure, so it is at liquid state. When the inflation is triggered and the percussor is removed, the cylinder is put in communication with the airbag chamber, so CO_2 suddenly evaporates and flows through the percussor hole in the chamber which is at almost ambient pressure. This sudden pressure reduction leads to a great temperature decrease; the cold CO_2 in the chamber is after quickly warmed again trough the contact with the chamber tissue and the ambient, so pressure in the airbag continues to rise even when all the gas in the cylinder already flew in the chamber. Given the cumulative mass of CO_2, several simulation, acting on the mass flow and gas temperature, were performed to adjust inflation parameters and achieve a good match

with experimental inflation data, both on pressure and on time, obtained from three pressure sensors disposed on the device during an inflation.

SIMULATIONS

Simulation strategy

Two simulation scenarios were chosen to evaluate behavior and performance of the airbag and its real effectiveness in reducing accident consequences for bikers: one for back impact and one for frontal impacts. Both of these scenarios are intentionally very simple, to keep the number of influent parameters as low as possible and enlighten at best the characteristics of the device.

Within each scenario, simulations were performed in MADYMO environment, at various impact speeds, to detect any eventual change induced by accident severity on the behavior of the airbag. Every simulation has also been performed with the dummy wearing no airbag, to get a comparison to evaluate device effectiveness.

After the study of the airbag "as it is", the hole optimization phase was begun. For each scenario, the simulation with the higher impact speed was appointed as reference and repeated with several configurations of holes in the airbag, to investigate the influence of hole position. The three brightest positions were pointed and passed to the following phases. First, a study on opening pressure of the holes has been performed, and after, using the most effective opening pressure found, for each hole position, a final study has been carried out on the area of holes. So, for each position of holes, the best hole characteristics, area and opening pressure, was found. These three configuration were confronted among themselves and the optimal solution has been found. Once found the optimal hole configuration, all simulations were repeated, in all scenarios and speeds, with the holed airbag.

Back impacts

In these simulations, the dummy model, wearing an helmet and the airbag and in the same position that it assumes on the motorcycle, is put at 1 m over ground and rotated 90° to orient the back downwards. Different initial speeds were assigned to the dummy, to reproduce falls from increasing heights, to a maximum of 2 m; this latter case was chosen as reference in the holes optimization phase.

Without the airbag, the first impact of the dummy on the ground occurs in the lumbar zone, after this first contact the dummy rotates the back downwards. This forces the head to hit the ground and, at the same time, the pelvis is projected upwards. The highest accelerations of thorax and pelvis are those caused by the first contact with ground, while the severest solicitations for head and neck come from the second part of the accident (Figure 4, upper row).

The presence of the airbag moves the point of first contact with ground to a slightly upper part of the back. This induces modifications in accident dynamics, thus the pelvis leans downwards after the first contact and is not projected upwards when the back rotates and hits the ground (Figure 4, lower row). Both thorax and pelvis acceleration are reduced, but on pelvis the reduction is greatly higher, 60% (Figure 5) against 20% (Figure 6), because of the translation of first contact point. The device also dumps some of the impact energy, so the back rotation is slower, leading to lesser head acceleration, and lower HIC values, with a mean reduction of about 50% (Figure 7). Finally, the presence of a gas volume behind the nape, together with the slowing of back rotation causes a great reduction (50%) of shear force acting on the neck (Figure 8).

Beyond percentage reduction, the effect of airbag on HIC, neck shear force and neck flexion torque is really important because in case of falls from heights over 1,50 m without the protective device, solicitations estimated by numerical simulations exceed threshold values proposed by UNE 135900:2008, while, in simulations with the airbag, all solicitations remain below the abovementioned thresholds.
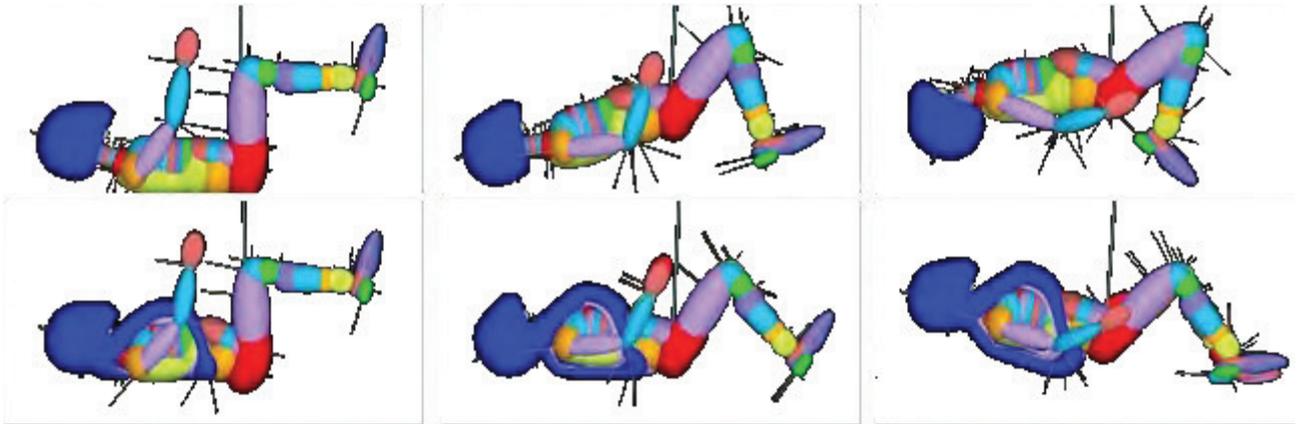
Figure 4 Back impact sequence, without and with airbag, 175, 225, and 275 ms after airbag firing. Equivalent fall height, 2 m., airbag is triggered 1 m above ground.
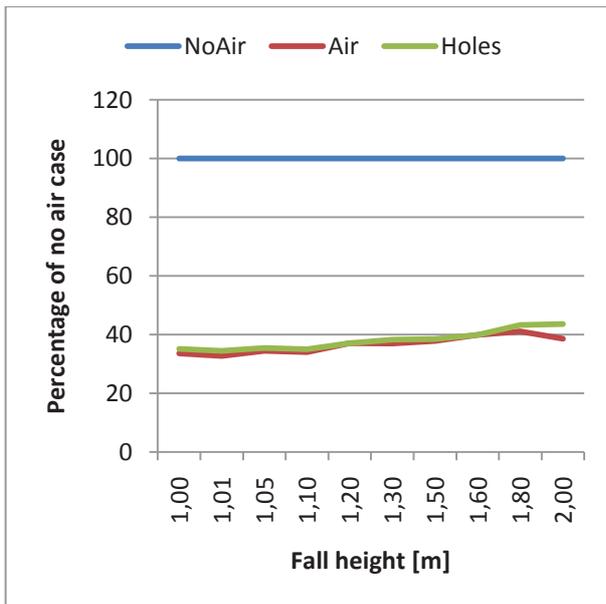

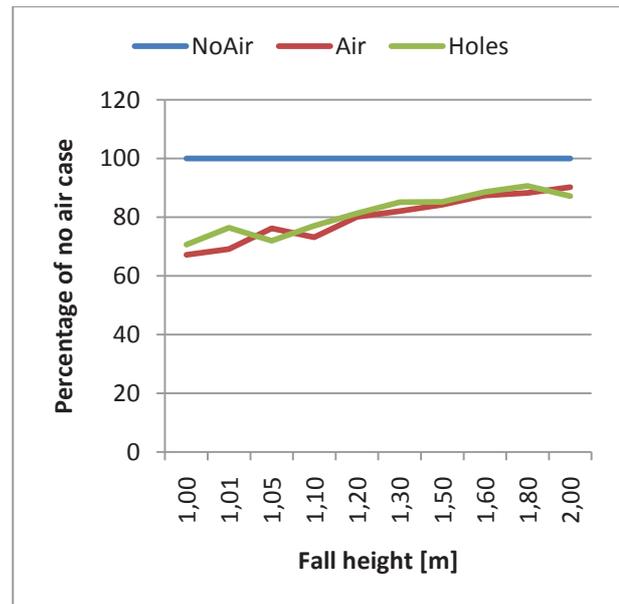Figure 5. Back impact - Pelvis acceleration

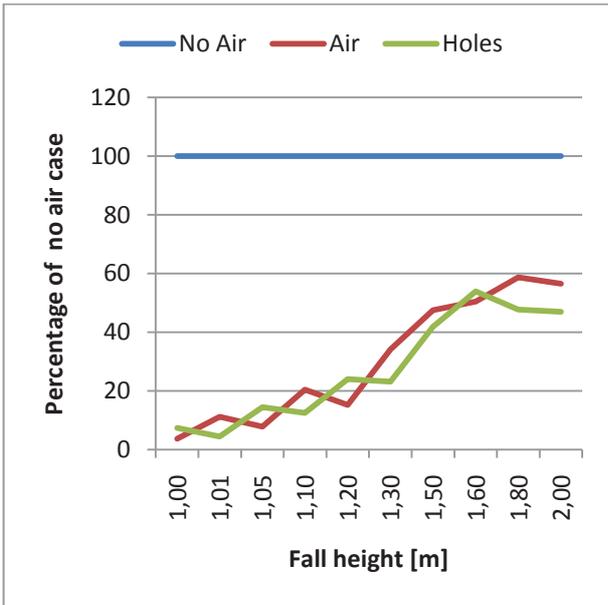Figure 6. Back impact - Thorax acceleration
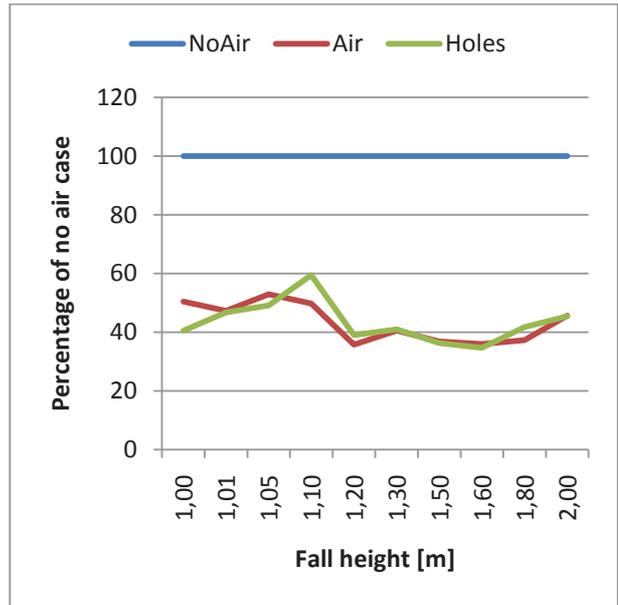
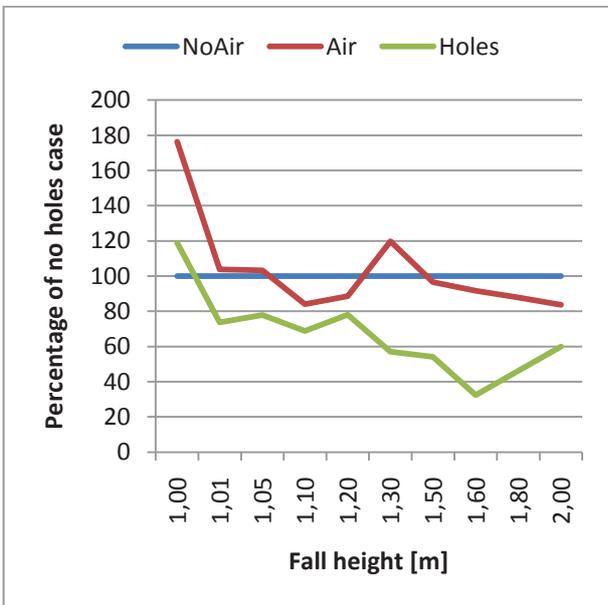Figure 7. Back impact – HIC

Figure 8. Back impact – Shear force on neck
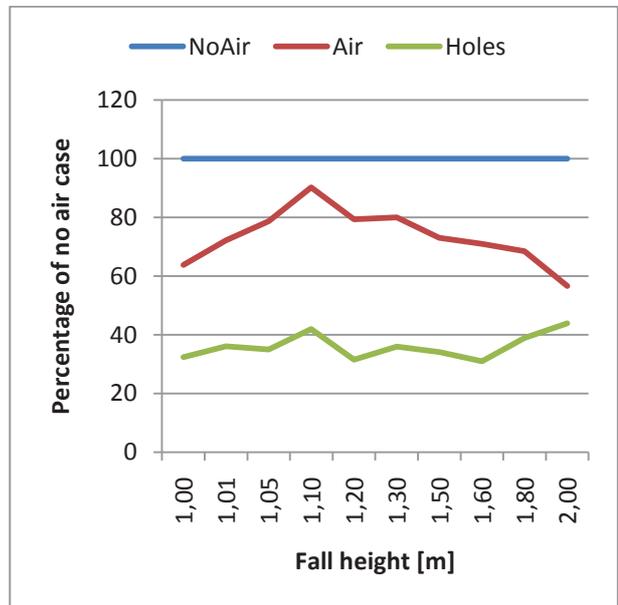

Figure 9. Back impact - Extension torque on neck
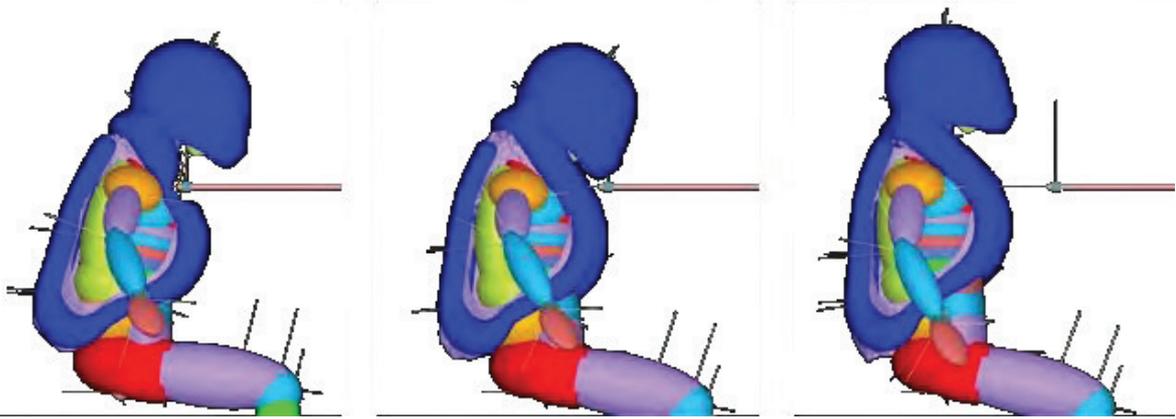

Figure 10. Back impact – Flexion torque on neck

Figure 11. Front impact (percussor diameter 80 mm, percussor speed 30 km/h) – Impact sequence, 150, 200 and 250 ms after the firing. The airbag is triggered when the percussor is 1,35 m away from the chest of the dummy.
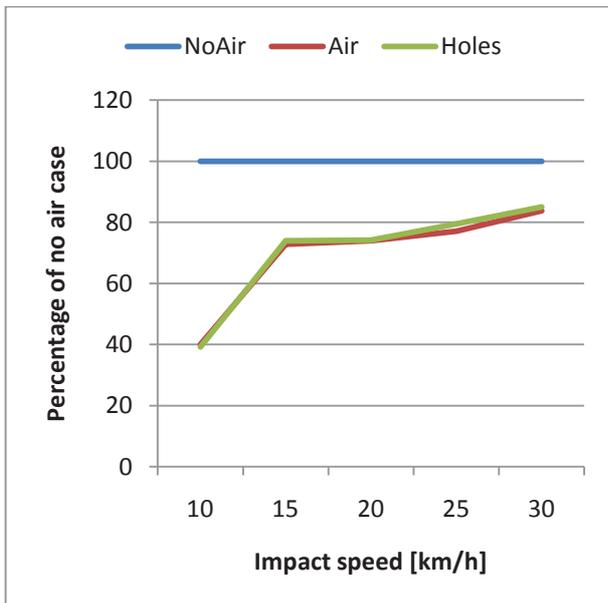

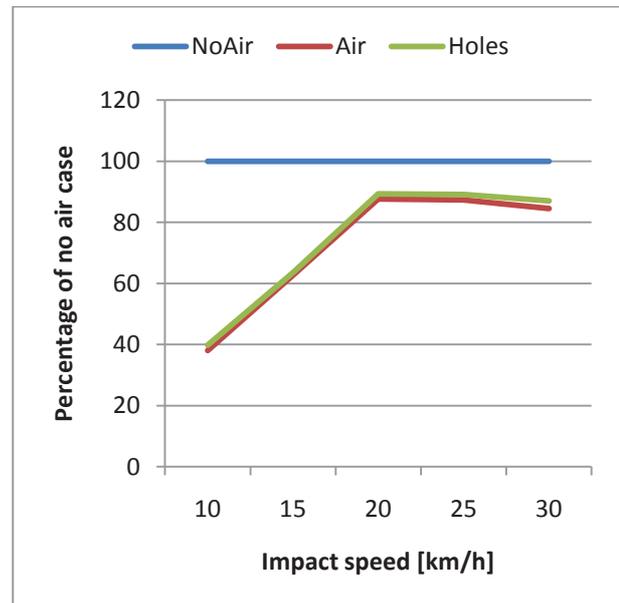Figure 12. Front impact (40 mm) - CTI

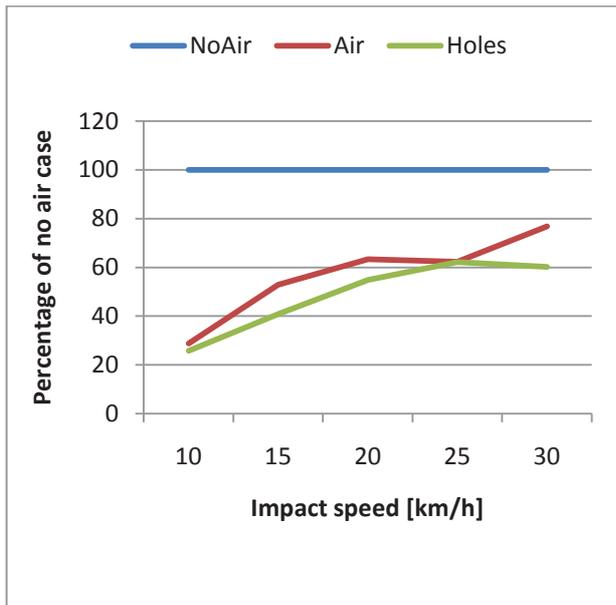Figure 13. Front impact (40 mm) - Shear force on neck

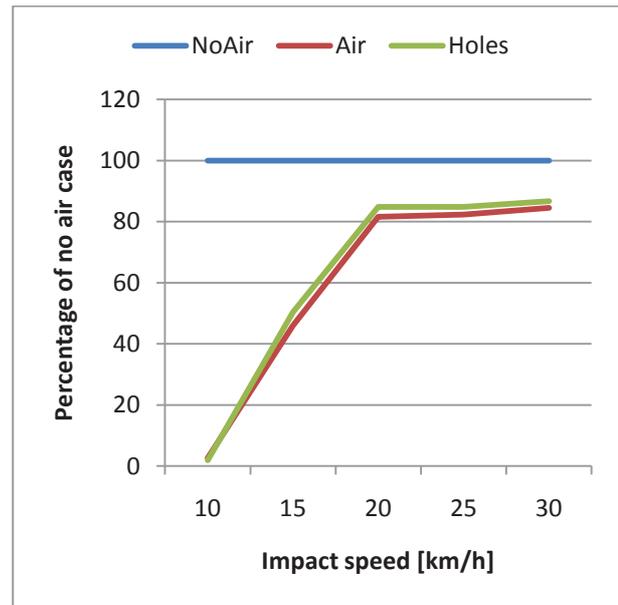Figure 14. Front impact (40 mm) - Extension torque on neck

Figure 15. Front impact (40 mm) - Flexion torque on neck

Front impacts

To simulate a frontal impact, the dummy, sitting on the ground and wearing helmet and airbag, is hit by a percussor on his chest. The percussor has a cylindrical shape, and its axis is horizontal and parallel to the shoulders of the dummy, while the approach trajectory is perpendicular to them. The percussor is 1 m long, enough to guarantee that impact involves the full width of the chest, and has a mass of 12 kg. The mass value was chosen according to previous studies on airbag devices intended to be worn by a motorbiker [5]. Regarding the diameter of the cylinder, three different measures were considered: 40, 80 and 120 mm. The impact speed range from 10 to 30 km/h by steps of 5 km/h. As for back impacts, the severest condition of 30 km/h impact was taken as reference for the holes optimization phase.

The percussor hits the upper part of the chest, that is pushed backwards; for inertial effects, the neck initially bends frontwards, bringing the chin near to the thorax, while in a second phase is drawn in a backward extension by the movement of the chest (Figure 11).

The introduction of the airbag into this scenario, leads to a general reduction of injury indexes, though this is not so great than in back impacts, it's still present and appreciable. This is an interesting result because the device was designed to protect neck and lumbar spine in rear impacts, so this simulation represent an off-design condition.

CTI (Figure 12) draws a constant benefit from the presence of the airbag, with a reduction of about 20%, but for higher speeds combined with grater percussor diameters. In these latter cases, the percussor covers almost all the part of the chest protected by the airbag and has enough energy to fully flatter the device, so there's no room for damping or re-distributing the impact force.

Regarding shear forces on the neck (Figure 13), they tend to pull the head away from the thorax in frontward direction, and the airbag is not very close to the neck in that direction. Nevertheless, a mean reduction by 20% of shear forces is however achieved, mainly thanks to the smoother body movement.

Finally, also a reduction of torque acting on the neck is achieved, both in extension (Figure 14) and in flexion (Figure 15). During neck extension, the helmet engages the airbag, establishing a rigid ensemble that grants a 50% mean reduction on extension torque. In forward flexion, the helmet-airbag interface is lower, so the ensemble is less rigid and the torque reduction is of about 35%.

Simulations proved that solicitations on neck, both shear force and torque, are the most harmful in this scenario, with thresholds proposed by UNE 135900 exceeded even with middle range impact speeds, so, even a slight reduction induced by the airbag could prove really effective in terms of avoiding serious injuries from an accident.

Holes

An accident involving motorcycle occupants could have characteristic times sensibly longer than a typical automotive accident; for example in case of a stand-alone fall with subsequent sliding on ground and hit against an obstacle on the road side. So, there are situations, that must be taken into account, when the airbag is triggered by the first impact but the main impact, the one which causes the most severe injuries, occurs only after a certain amount of time. In such cases, an airbag with free holes, as common in automotive realizations, could be almost deflated and ineffective at the moment of the main impact. In this study, airbag with "rupture holes" were studied. These holes open only when pressure grows over a prescribed pressure value, so the airbag remains inflated at the desired pressure until an impact occurs.

The chamber volume of the investigated device is quite small, so holes must have a very small area and must open only when a certain pressure is reached, otherwise the airbag could face the impact result too deflated to be effective. Even with these characteristics, the effects of the holes on the device performances are less significant than in other airbag applications. Despite of this, with ad adequate set up of holes position, area and opening pressure, some improvements are achievable.

With a hole near the zone hit by the percussor, the airbag is subjected to an excessive deformation and is fully flattered during front impacts, losing its performance. So, the best position for holes resulted to be on the lower extremity of the lumbar zone. After the optimization phase, an opening pressure of 45000 Pa was chosen, for both the 1 cm^2 holes. In this configuration a slight reduction in neck extending torque during the frontal impact is achieved (Figure 14), while the other injury indexes show almost no variations for that accident. The same configuration grants some more advantages in back impacts, where the torque acting on the neck, both in extension (Figure 9) and in flexion (Figure 10) is reduced by 30 and 50%.

Accident reconstruction

After back and front impact simulations, the airbag has been evaluated also in a motorcycle versus car accident scenario amongst those prescribed by ISO13232:2005. In this scenario (n° 413, Figure 16), the motorcycle hits, with a 90 degree angle, the side of a standing car. The initial velocity of the motorcycle is 13,4 m/s (about 48 km/h) and the prescribed point of impact is exactly in the middle of the silhouette of the car. The same accident has been investigated also for lower speeds, to a minimum of 30 km/h.

The car model, is a Finite Elements (hereinafter FE) model of a Dodge Metro, this model is from NCAC vehicle database, was originally created for LS-DYNA applications and after it has been adapted to MADYMO environment.

The motorcycle model is not an FE model but a facet MADYMO model of a Piaggio Nexus scooter. A facet model is a multibody model, composed by rigid bodies, with assigned inertia and contact properties, whose surface is not defined by mathematical surfaces but via finite elements. This modeling technique allows a very good shape reproduction together with limited calculus resources requests. The contact characteristic of the front part of the model was adjusted during previous activities of CISAP (Center for Innovation and Safety of Powered two wheelers), via numerical simulations and matching with experimental data [11].

The activation wire is modeled with a strap, which extends from the motorbike chassis to the percussor on the airbag. A strength sensor is put on the strap, when the tensile strength rise above the prescribed value, the strap is removed and the airbag inflation is triggered. In all the simulations performed, the activation system was effective and quick enough to inflate the airbag before the dummy contact with the car, which occurs at least 80 ms after the device trigger, depending on the speed and consequent accident dynamics.

Since this scenario (Figure 17) is really more complex than the previous two, also the results are complex, and their interpretation is not very easy. Generally, the presence of the airbag provokes a re-distribution of the impact energy between head and neck. The first part of the body to hit the car is the head; the point of impact is remarkably afflicted by speed and can move from the side of the door to the ceiling. Subsequently the head, if it hit the upper part of the car, slides on the ceiling, bringing the thorax in contact with the side of the vehicle. When the airbag is inflated, it generates a volume in front of the chest that anticipates the thorax contact with the car and is loaded by a greater part of the impact energy.

On HIC, the effect of the airbag is a general reduction (Figure 18), especially for higher speeds, where, thanks to the particular accident dynamics which forces the neck to extend backwards, there are also benefits from the rigid ensemble formed by the airbag together with helmet and shoulders.
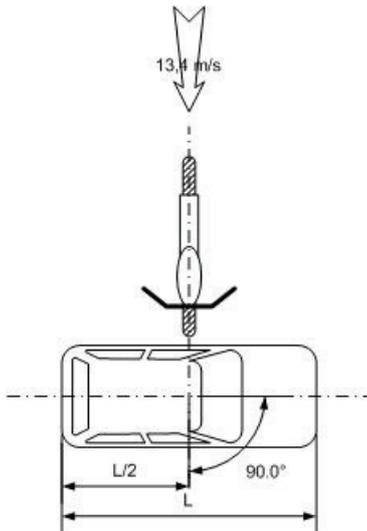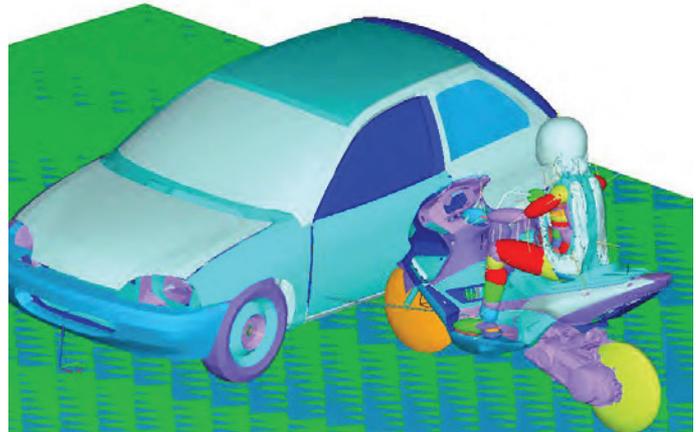
Figure 16. ISO 13232, scenario 413
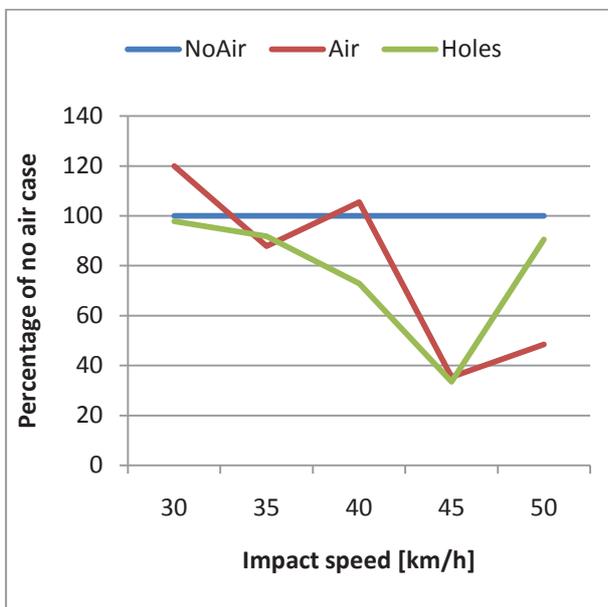

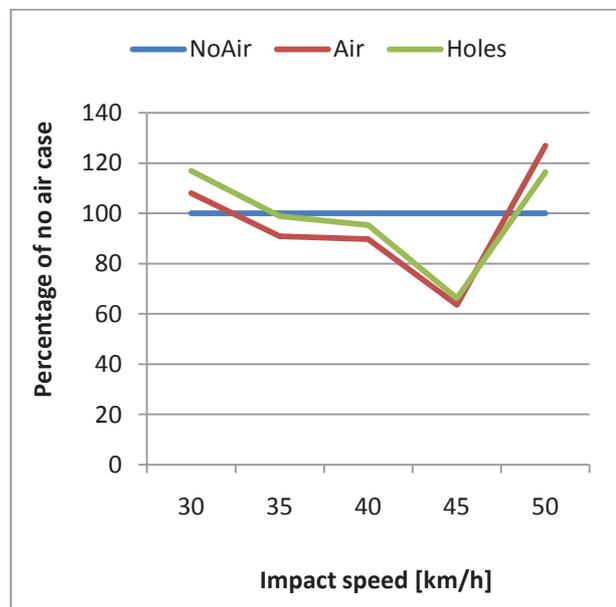Figure 17. Accident reconstruction

Figure 18. ISO 13232 - HIC

Figure 19. ISO 13232 - CTI

Regarding CTI (Figure 19), the effects of the augmented impact load are generally balanced by damping effects and re-distribution of load on larger surface, and the result is a slight CTI reduction. Only for higher speeds, the impact energy is so high to fully flatter the air chamber, and CTI is almost equal to the no airbag case.

CONCLUSIONS

Numerical simulations were performed on a wire-triggered airbag device, fitted in a jacket, in order to estimate its performance during an accident. Two ad hoc simple scenarios were used to investigate the device behavior in two different, and quite opposed, kind of impact. Moreover, the behavior of the airbag has been investigated also in a more realistic accident scenario, from those proposed by ISO 13232:2005 and involving a motorcycle impacting on a standing car side with a 90° angle.
Performed studies allowed to gather skills and knowledge on effectiveness evaluation of small airbags to be worn by a rider and on optimization of hole number and dimensions for energy dissipation.
Results showed that the presence of the airbag leads to advantages in reducing the severity of injuries induced by some accidents, increasing impact surface and so re-distributing the force exchange on a wider body portion, provided that the impact occurs in a zone protected by the device. In such cases, the presence

of the airbag also leads to an increased impact time, lowering both the peak value of the force and the mean deceleration imposed to the biker. Through some appropriate holes the airbag is also able to dissipate part of impact energy that otherwise would be absorbed by human body. The particular shape and ergonomics of the airbag seems really effective both during collisions with other vehicles and stand-alone sliding, since it follows and defends the biker against secondary impacts. So, the employment of airbag technology could prove itself to be really effective and play a decisive role in reducing injuries suffered by a motorcyclist during an accident.

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