A Parametic Study of a Side Airbag System to meet Deflection Based Criteria

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Abstract

A side airbag system comprising a 12 litre bag to cover the chest and the abdomen down to the arm rest level and 75 mm of padding to cover the pelvic/thigh area was evaluated by a series of sled tests at two different velocities, 10 m/s and 12 m/s. The initial bag (over) pressure was varied from 0 to 80 kPa and the bag ventilation area was varied from zero to 1500 mm^2. Compressed air was used to fill the bag.

It was found that the ventilation of the bag reduced the maximum chest deflection by 30% and the maximum viscous criterion, VC, by 50% (comparison was made with the same bag without ventilation). A suitable initial bag (over) pressure was found to be about 40 kPa, when also the the loading of the abdomen was taken into consideration.

The results indicate that the chest deflection is proportional to the door average velocity (during the first 20 ms of deflection) to the power of about 2 and that the VC is proportional to the same velocity to the power of about 4.

It was also found that a 12 litre ventilated side airbag resulted in 30–40% lower chest deflection and about 60% lower VC than 50 mm chest padding (Ethafoam 220).

Introduction

Several investigations have shown that side impacts are more severe from life threatening point of view than frontal impacts. Injuries are about twice as common to struck side occupants as to non-struck side occupants (Håland et al., 1990). Efforts to improve the side impact protection are therefore concentrated on the struck side occupants.

Accident data (Harms et al., 1987) shows that 90 % of all side impacts with various occupant injury outcomes occur at impact speeds below 35 mph (56 km/h). About half of the severe to fatal injuries are incurred below this speed. The procedures for side impact tests in the United States (NHTSA, 1990) and Europe (ECE, 1991) prescribe impacts with mobile deformable barriers at 33.5 mph (54 km/h) and 50 km/h respectively, which seem to represent an average side collision from life threatening point of view. A 50 km /h (30 mph) full frontal collision into a stiff barrier results in a higher delta v for the tested vehicle. However, the frontal structures of a modern passenger car can absorb an energy up to 5 times higher than the side structures (Cesari and Block, 1984).

The American and European side impact procedures differ not only with respect to the mobile barrier but also to the test dummies and the injury criteria. The evaluation of chest injury is difficult. The American regulation uses TTI, an acceleration based criterion, whilst in Europe VC (viscous criterion or viscous response), which is a deformation based criterion, will be used. The viscous criterion is the result of work performed by Lau and Viano (1986).

In a side impact, the energy transferred to the struck side occupant is highly dependant on the interaction with the door. The occupant is punched by the encroaching door (Lau et al., 1991). The velocity time history of the door, the occupant location relative to the door and the shape and compliance of the interior all affect the injury risk. Reinforcement of the car structure (Mellander et al., 1989) to reduce the door to occupant impact speed, and to avoid a collapse of the B-pillar (de Coo et al., 1991) is the first and necessary step in improving the occupants's protection. The next step in improving the door to occupant interaction is to use some suitable bolstering. Padding is one type of bolstering and an airbag another.

Håland and Pipkorn (1991) found that a combination of an airbag in the chest/abdominal area and thick soft padding in the pelvic/thigh area (a side airbag system developed by Electrolux Autoliv) gave a considerable improvement in the protection of all body segments of the struck side occupant in car to car side impacts. Chest injury criteria like TTI and VC were significantly lower with an 8 litre airbag compared with 50 mm thick padding in sled tests simulating a 50km/h (30mph) side impact into a well reinforced car.

In the latest version the side airbag has a volume of 12 litre and a length of about 450 mm to be able to protect occupants of different sizes, with the seat in the most rear to the most forward position (figure 1). Two small and very fast gas generators, of the same type used for pyrotechnical pretensioners but with a larger pyrotechnic charge (in total 4 g), are used.

The bag must be fully inflated within 10-12 ms, while there still is about 100 mm clearance between the door inner wall and the occupant's chest. The bag inflation takes 7-8 ms with the type of gas generators used. This means that a sensor must trigger the system within 2-5 ms after the initial impact.

A sensor for a side airbag system can't be centrally localized in the car. An undeformed part of the car won't start to move until 7–10 ms after first car-to-car contact (Friedel, 1988). The sensor must be located close to the outer surface of the car. It must also be placed close to the occupant, since over 80% of the life threatening injuries in the near side impacts are connected with door intrusion close to the occupant (Hartemann et al., 1976; Harms et al., 1987).

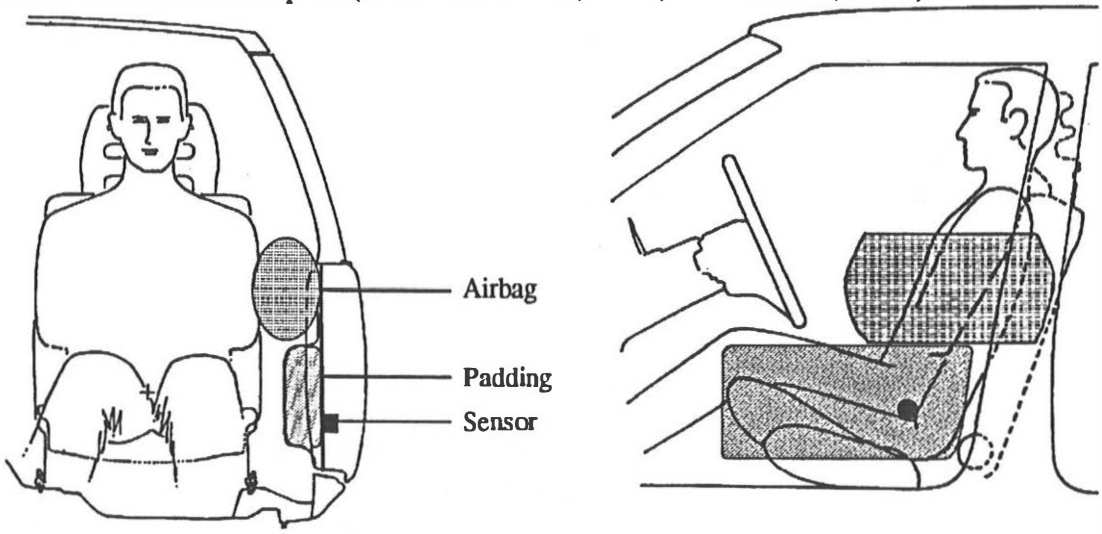

Figure 1. Airbag and padding in the door (Electrolux Autoliv).

Electrolux Autoliv has chosen a pyrotechnical, non-electrical, sensor (figure 2). The sensor is located in the lower rear part of the door, 30–40 mm inside the door outer skin and will only trigger in the case of door intrusion with a risk of personal injuries and not in the case of, for example, parking damage or low impact speeds. The sensor element is a percussion cap that fires above a certain impact speed. Within 1 ms from sensor contact the flame from the percussion cap has been distributed to the two gas generators by means of shock tubes (Nonel).

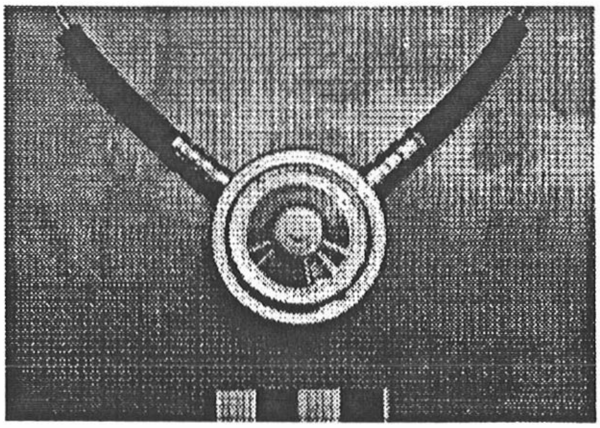

Figure 2. Pyrotechnical side impact sensor (40 mm diameter).

Thick and soft padding can be used below the armrest level in the door without infringing on the space for the occupant's arm. About 75 mm of padding in the pelvic/thigh area seems to be acceptable to car makers. A suitable padding material is of a soft polyethylene foam type with open cells and a density of 30-40 kg/m^3. Its characteristic is between constant stiffness and constant crush force (Pipkorn, 1992). The energy absorption is good, at about 70%.

The chest of a struck side occupant is loaded by the intruding door with a speed that is higher than that which a belted occupant is loaded by the belt in a frontal impact. The injury causing mechanisms are therefore different. The speed of the intruding door, at the time of contact with the occupant's chest in a 50 km/h (30 mph) car to car side impact, can be in the range 8-14 m/s. The chest then behaves with a visco-(elastic) response. This viscous response is the instantaneous product of the chest deformation velocity and the chest compression during the impact. The proposed injury criterion is $VC \leq 1$ m/s. This is included in the proposed European side impact regulation. The chest criterion TTI (thoracic trauma index), which is included in the American regulation, is the average of the maximum spine acceleration and the near-side rib acceleration, both in g's. The calculated TTI-figure shall be below 85-90 g (for four and two-door cars respectively). Which injury criterion is most relevant to use, TTI or VC, is controversial. A side impact protection system, for example a certain padding, can reduce TTI but not necessarily VC (Deng,1989).

In a side impact, chest and abdominal injuries occur when the stationary occupant is "punched" by the encroaching door (Lau et al, 1991). Padding provides an earlier and longer contact with the encroaching door. Acceleration based criteria like TTI can be reduced by padding, due to decreased rib accelerations. Deformation based criteria like VC and chest deflection can actually increase due to the prolonged punch and an increase in net energy transferred to the occupant. In a series of side impact tests in the USA with baseline and padded cars (with 75 mm of "medium" stiff padding on the inside of the door) the TTI-figures recorded were 25% lower in the padded cars, whilst the maximum chest deflection was on average 35% higher (Wasko et al, 1991).

The padding must physically be softer than the human torso to compensate for the prolonged door contact. There would be a net reduction in chest deflection if the padding causes the spine to move from the door fast enough to compensate for the padding thickness. A reduction in chest deflection that is larger than the "bottoming out" thickness of the padding is possible. If the padding on the other hand is stiffer than the torso, the chest deflection (and VC) will increase instead of decrease.

Biomechanical research (King et al., 1991; Cavanaugh et al., 1992) has shown that padding of 20 psi (140 kPa) crush strength was tolerated by the thorax of subjects in their twenties to forties but not by those in their fifties and sixties. Aortic lacerations occured in some tests. To protect these age groups materials of 8 - 15 psi (55-105 kPa) crush strength are required and have been found to markedly reduce thoracic injuries. The pelvis was found to tolerate padding of 40 psi (275 kPa) crush strength.

It is easier to reduce the acceleration based criterion TTI than to reduce the deformation based criteria (chest deflection and VC). The most effective way to reduce TTI is to make the initial door to rib cage contact softer. A typical rib acceleration time curve has two peaks. The first peak, and normally the largest, takes place during the initial contact with the padding and the second peak comes when the padding bottoms out. The initial gradient of the padding can be optimized to lower TTI. A suitable padding stiffness is of the order of 50-100 kN/m (measured with a flat 150 mm diameter impactor surface) (Deng, 1989). 50 mm of padding in the chest area seems in most cases to be sufficient to lower the TTI figures below the American requirements provided that the car side structure has been well reinforced.

A padding thickness of 50 mm on the inner surface of the door at chest level is the maximum possible in most cars. This may not be thick enough to come below the deflection based chest injury criteria according to the proposed European side impact regulation, even when the car structure is well reinforced. The next step is to fit an airbag instead of padding.

Airbags can be considered as one type of bolstering to improve the door/occupant interaction in a side impact. An airbag can more easily be made physically softer than the human torso than padding to compensate for the prolonged door contact. An airbag could also be made thicker in the chest area than padding. This will increase the possibility to move the occupant further laterally before the deformation based values reach their maxima.

Head impacts with the A- and B-pillars and the roof rail can be made less severe if the potential impact areas are covered by, for example, 25 mm of rather stiff padding. A crush strength of 40 - 60 psi (275-410 kPa) is suitable and can keep HIC below 1000 units at head impact speeds up to 6.7 m/s (15 mph) according to American test results (Monk and Sullivan, 1986). A head to B-pillar impact may happen in side impact tests according to the European regulation with some 4-door cars, but it is unlikely to happen in tests according to the American regulation. The American mobile barrier impacts at an angle that will give the head a slightly forward trajectory.

The life threatening head ejection outside the side window is also decreased or eliminated with the chest airbag/pelvic padding concept due to the earlier lateral movement of the occupant. The reduction of the head displacement (relative to the car) is typically in the order of 30 mm. (Håland and Pipkorn, 1991).

The aim of this study was to evaluate the effect on deflection based chest injury criteria of various parameters in a side airbag system. The evaluation was performed by sled tests simulating side impacts of different severities.

Method

In the proposed European side impact regulation there are two deflection based criteria specified for the chest; the viscous criterion VC must be less than 1 m/s and the chest deflection less than 42 mm. The study focused on these criteria.

Pre–inflated airbags filled with compressed air were used in the sled tests. The bags were 12 litre in volume. The initial gas pressure could easily be changed with a normal air regulation valve.

The ventilation of the bag was achieved by a specially developed fast opening valve in the bag housing. By rotating the valve body 90 degrees a ventilation area of about 1500 mm^2 was achieved. The supply of compressed air to the bag was stopped at the same moment the ventilation valve was activated. The valve was fully open, when there was a distance of 200 mm between the door inner wall (the black inside of the door in figure 4) and the chest of the test dummy.

The pelvic/thigh area was protected with 75 mm thick padding of polyethylene type foam (Ethafoam 220). This padding material has an energy absorpation of about 70%, and a progressive characteristic. The same type of padding, but 50 mm thick and about 125 mm high and located in the chest area (with a recess in the door for the arm elbow above the pelvic padding), was compared with the 12 litre airbag. The padding stiffness, about 60-100 kN/m (for an impact area of 175 cm^2), was chosen based on the mathematical simulations reported by Viano (1987).

A sled test method that simulates full scale test conditions was used (Håland and Pipkorn, 1991). A reinforced door, mounted to a crash track sled, impacts a test dummy sitting on a seat at right angles to the crash track (figure 3 and 4). The door approaches the dummy at a constant speed and is then braked at a constant deceleration. The door velocity time history, the door average velocity during the first 20 ms of door padding or airbag to occupant interaction, simulates full scale test conditions. The 20 ms time interval includes the start of the chest deflection, the maximum chest viscous response and the maximum chest compression events. The sled tests were run at 10 m/s and 12 m/s door velocities. The door was braked with a deceleration of about 20 g when the door inner wall (the black inside of the door in figure 4) reached the dummy's shoulder.

The test dummy used was the BioSid. There are at the present time three side impact dummies available; US Sid, EuroSid and BioSid. The first one is prescribed in the new US regulation and the second one in the proposed European regulation. However, Bio Sid which is the latest of the three dummies, has the best biofidelity (ISO, 1990) and was therefore used in this study.

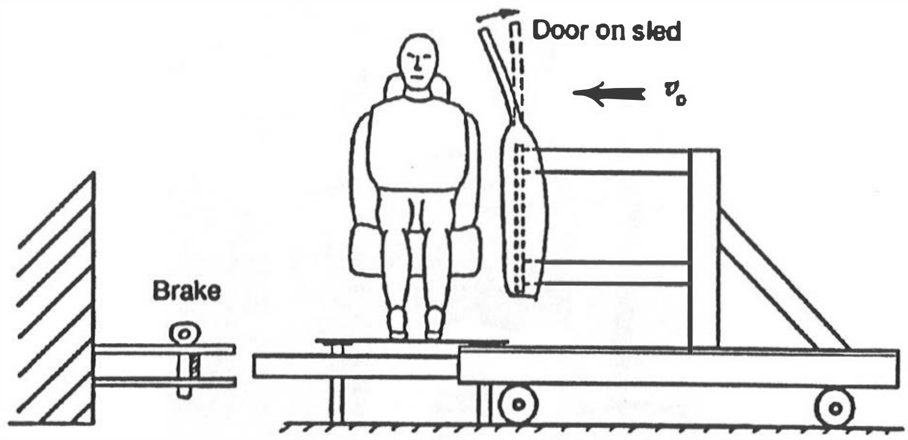

Figure 3. Door on sled impacting the dummy.

The sled tests were run at two door velocities, 10 m/s and 12 m/s, three different levels of initial gas (over) pressure in the bag, 0 kPa, 40kPa and 80 kPa, and with different ventilation areas 0, 1/2 and 1/1 of the maximum area 1500 mm². The test matrix can be seen in table 1.

Table 1. Test matrix of the sled tests.

Configuration	Door velocity (m/s)	Initial bag pressure (kPa)	Ventilation area*
121 airbag	10	40	0
	10	0	1/2
	10	40	1/2
	10	80	1/2
	10	0	1/1
	10	40	1/1
	10	80	1/1
	12	40	0
	12	0	1/2
	12	40	1/2
	12	80	1/2
	12	0	1/1
	12	40	1/1
	12	80	1/1
50mm padding	10	-	-
	12	-	-

* 1/1 corresponds to 1500 mm².

Each test combination was normally run only once. However, the tests at 10 m/s and 12 m/s, 40 kPa and 1/1 ventilation area were each run three times to study the variation in the results.

The deflection of the three thorax ribs of the BioSid dummy was measured. For the calculation of chest VC the unfiltered (CFC 1000) rib–to–spine deflection signal was differentiated to obtain rib–to–spine velocity. Both rib–to–spine deflection and velocity were then filtered by CFC 60, multiplied by each other and divided by 175 mm to obtain the viscous response (VC).

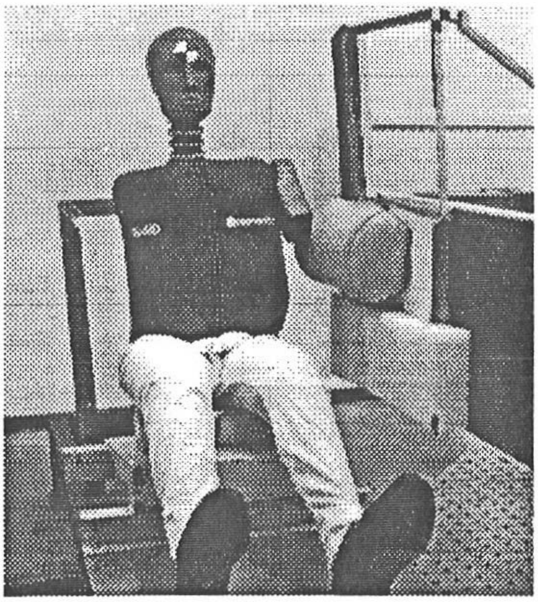

Figure 4. Sled test configuration - 12 litre chest airbag, 75 mm pelvis padding and the BioSid dummy.

Results

Side impact severity

The door impacted the dummy with a speed of 12 m/s in the more severe tests and with 10 m/s in the somewhat less severe tests.

The door average velocity in the 20 ms time interval, when deflection based criteria reach their maxima, was 10.6 m/s and 8.8 m/s respectively (figure 5). The more severe test intended to correspond to a 50 km/h side impact (car-to-car) into a car that is not too well reinforced, whilst the somewhat less severe test at the lower velocity corresponded to the conditions for a well reinforced car. The 12 m/s test could also represent a 55-60 km/h side impact into a well reinforced car. These estimations are based on information from some car makers.

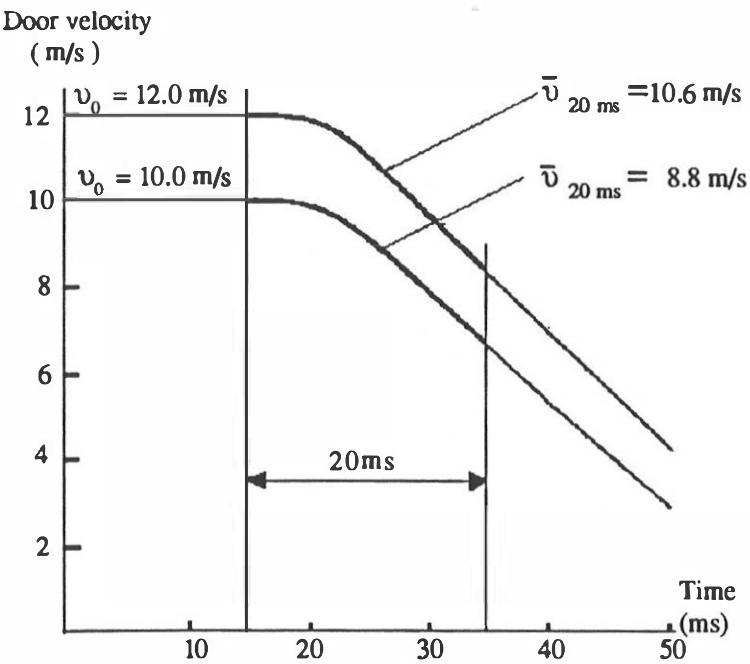

Figure 5. Side impact severites, typical door velocity time histories in the sled tests.

Initial bag (over) pressure and ventilation

The results of the tests with the 12 litre air bag can be found in figure 6 and 7. The first figure shows the maximum chest deflection (average value form the three ribs) versus ventilation area at the two door velocities, 10 m/s and 12 m/s and at 0, 40 and 80 kPa initial bag (over) pressures. Figure 7 shows in the same way the maximum chest viscous response (VC).

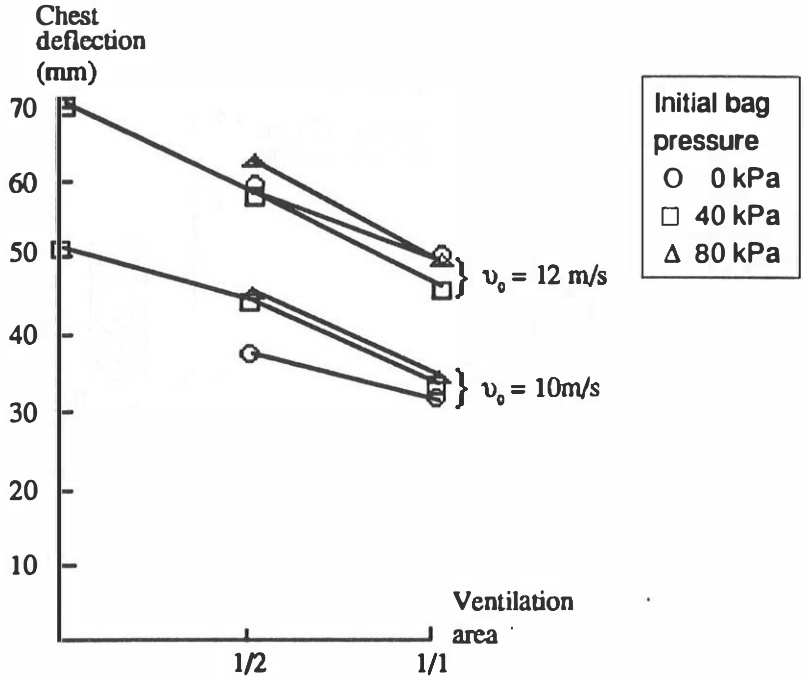

Figure 6. Chest deflection versus ventilation area and initial bag (over) pressure (N=1).

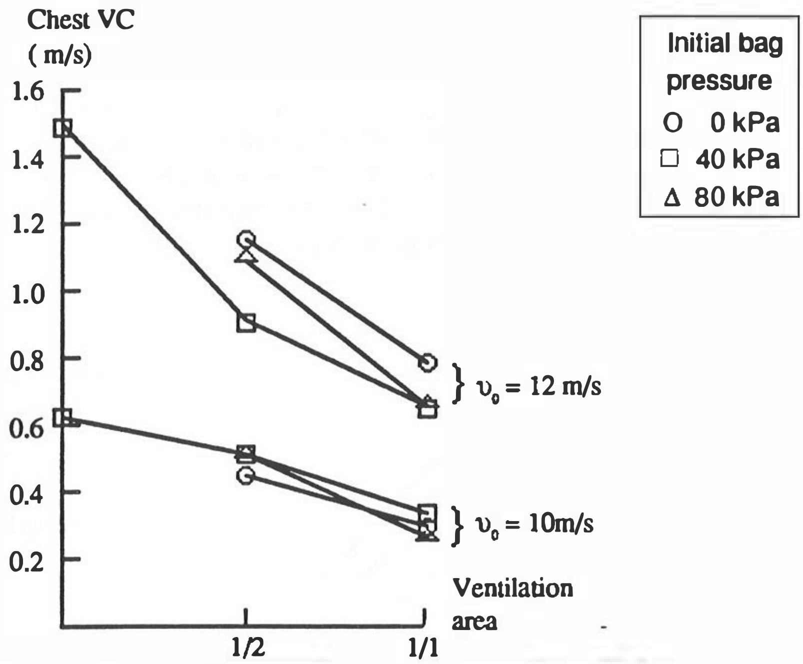

Figure 7. Chest VC versus ventilation area and initial bag (over) pressure (N=1).

The chest deflection decreased (at 10 m/s and 40 kPa) from 51 mm at no ventilation to 33 mm at full ventilation area. The VC decreased during the same conditions from 0.6 m/s at no ventilation to 0.3 m/s at full ventilation.

The chest deflection at the 12 m/s door impact velocity, 40 kPa initial bag pressure and full ventilation area was 46 mm. The VC decreased with the same initial bag pressure from 1.5 m/s at no ventilation to 0.6 m/s at full ventilation.

The 95% confidence limits of the chest deflection was the mean value ± 4 mm. The corresponding 95% limits for the VC was the mean value ± 0.1 m/s. The differences in results (for chest deflection and VC) between the tests at 10 m/s and 12 m/s were statistically significant ($p<0.01$).

The results with the 50 mm chest padding configuration can be found in figure 8 together with the results with the 12 litre air bag at 40 kPa initial bag pressure and full ventilation area.

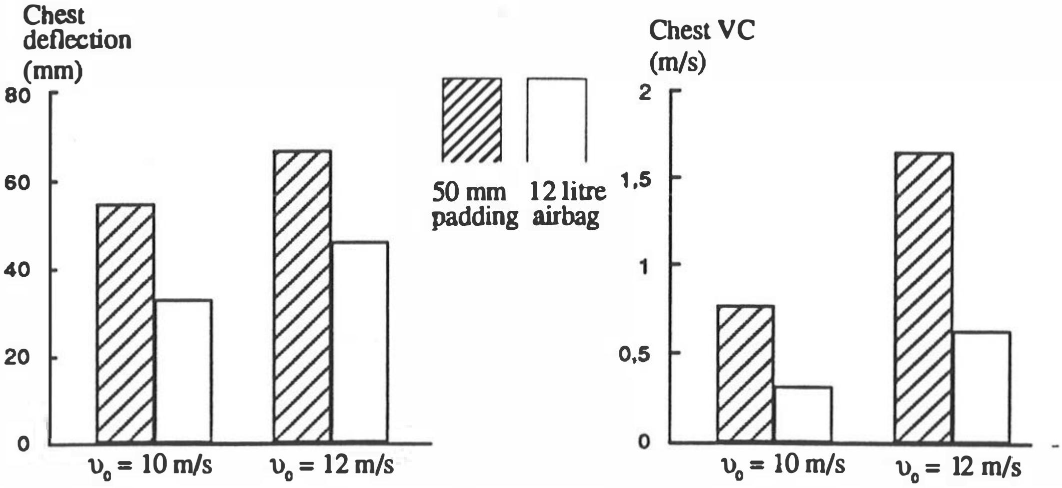

Figure 8. Chest deflection and VC for 50 mm chest padding and 12 litre ventilated air bag (N=1).

The 12 litre airbag resulted in about 20 mm (30-40%) less chest deflection on average than the 50 mm chest padding. The differences in viscous response (VC) were large. The VC with the air bag was at about 40% of the VC obtained with padding at both test velocities. The differences in results between the padding and the airbag were statistically significant ($p<0.001$).

Discussion

The results form the sled tests (figure 6 and 7) show the importance of bag ventilation to reduce the chest deflection. However, the maximum ventilation area with the present valve seems not to be large enough. There is a further improvement possible for an optimum system.

An initial bag pressure of 40 kPa gave the lowest chest deflection and the lowest VC at the 12m/s door velocity. The deflection and the VC increased, when the initial bag (over) pressure was lowered to 0 kPa at 12 m/s. The testresults at 10 m/s and full ventilation area do not give an answer, which initial gas pressure that is the optimum. However, if also the abdominal viscous response at both 10 m/s and 12 m/s and full ventilation area is taken into consideration (figure 9), it is obvious that the initial bag pressure shall not be as high as 80 kPa.

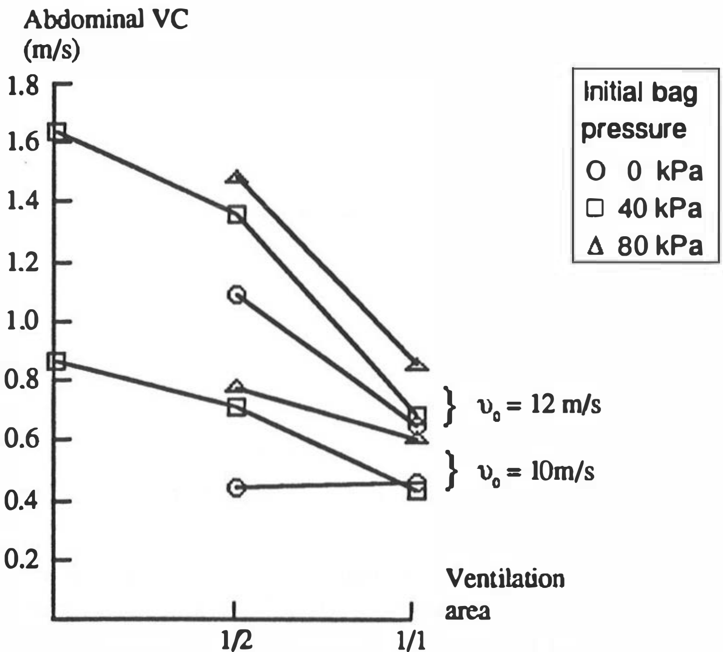

Figure 9. Abdominal VC versus ventilation area and initial bag (over) pressure (N=1).

The BioSid dummy was at the upper end of the chest deflection tolerance interval at the calibration. This means that the chest was rather soft. This should be taken into consideration when the absolute levels of chest deflection are compared with the European criterion level of 42 mm.

The most critical parameter for the chest deflection is probably the door velocity time history during the first 20 ms of deflection. It is a measure of the violence transferred to the chest of the occupant. An average door velocity in the 20 ms timer interval, $\bar{v}_{20ms}$ (figure 5), has been defined as a respresentative measure of the door velocity time history.

The results in figure 6 and 7 indicate that the chest deflection is proportional to $\bar{v}_{20ms}$ to the power of about 2 and that the VC is proportional to $\bar{v}_{20ms}$ to the power of about 4. VC is thus very speed sensitive. Measures by car makers to reduce the door velocity time history is very important. It will probably not be possible to compensate a bad car structure with only bolstering on the inside of the door.

A side airbag can be made thicker (when inflated) in the chest area than padding. It is therefore easier to make the airbag physically softer than the human torso than padding. A padding will also bottom out more quickly. The results in figure 8 confirm this. The chosen padding material, Ethafoam 220, is softer before it bottoms out than the chest of the BioSid dummy but it is not thick enough, at only 50 mm.

It was known before the sled tests were undertaken in this study, that the repeatability of the results were good. Therefore, only one test for each test condition was run to enable coverage of a large test matrix. However, the repeatability was checked for two representative test conditions for the airbag (10 m/s, 40 kPa, 1/1 ventilation area and 12 m/s, 40 kPa, 1/1 ventilation area).

The bag volume in this study was 12 litre. It was increased from the earlier 8 litre. The reason for this was that the smaller bag in tests at 12 m/s door velocity resulted in 10–15 mm higher chest deflection. The 12 litre bag better covers both the chest and the abdomen down to the arm rest level. However, it is not believed that it would be beneficial to increase the bag size one step further.

To improve the side impact protection, an airbag must have a force deflection characteristic that matches the one of the car occupant (represented by the BioSid dummy). The bag must be somewhat softer than the chest. Otherwise the chest deflection will increase instead of decreasing. Drop tests with an impactor, with the same shape as the chest of the BioSid dummy, were therefore performed in order to characterize the 12 litre side airbag (figure10). The effective contact area between the chest impactor and the bag was found to increase from 400 cm^2 at the early penetration phase to 700 cm^2 when the bag bottomed out.

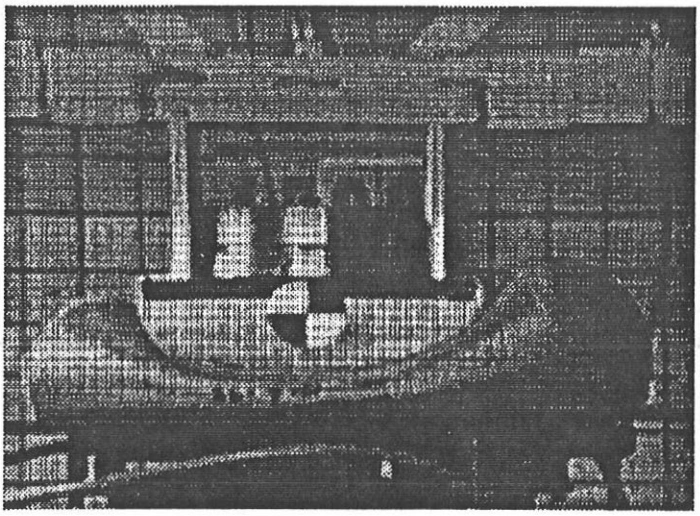

Figure 10. Drop test of a12 litre side airbag with a chest impactor.

Figure 11 shows the force - deflection characteristics the chest of the Bio Sid dummy at 6.7 and 4.5 m/s impacts by a 23 kg calibration impactor. The chest is stiffer at the higher impact speed.

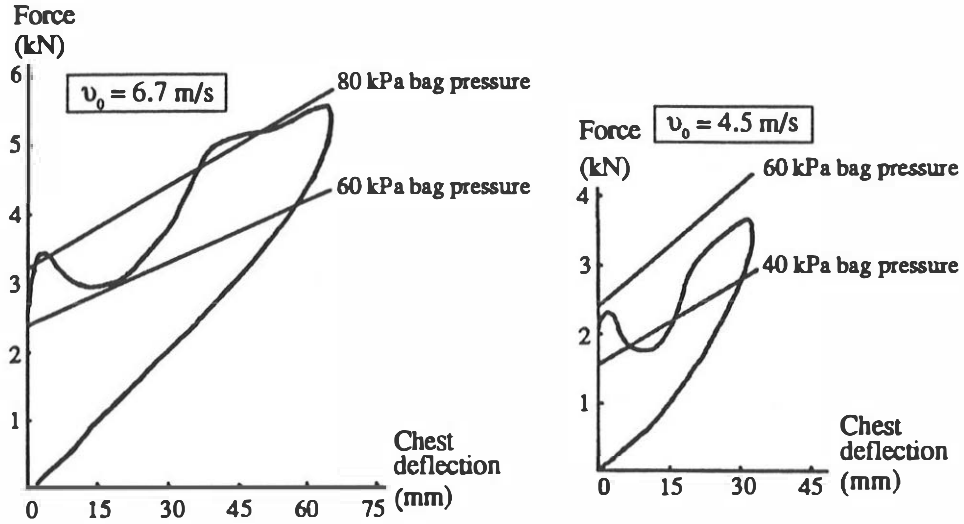

Figure 11. Force – deflection characteristics of the chest of the BioSid dummy and of the 12 litre airbag at different (constant) bag pressures.

The two straight lines in the left part of the figure represent the force deflection characteristics of the 12 litre airbag, when the internal gas pressure during the bag deflection is kept constant at 60 kPa or 80 kPa. It is assumed that the contact area (see above) increases linearly from 400 cm^2 to 700 cm^2 as the bag is compressed 100 mm. If the bag shall be somewhat softer than the chest during the whole deflection, the initial bag pressure should not be higher than 60 kPa and the final pressure, when the bag bottoms out, should be somewhat below 80 kPa. The righthand part of figure 11 shows in a similar way two constant bag pressure lines, when the chest deflection (the energy transfer) is less severe. The initial bag pressure in this case should be about 40 kPa.

The maximum bag pressure, just before the bag bottomed out and the maximum chest deflection was reached, was 95 kPa in the 10 m/s, 40kPa, 1/1 ventilation test and 110 kPa in the 12 m/s, 40 kPa, 1/1 ventilation test. The ventilation was thus a little insufficient.

Biomechanical research data from Wayne State University (King et al., 1991; Cavanaugh et al., 1992) says that 20 psi (140kPa) crush strength of padding can be tolerated by the thorax of people in their twenties to fourties and that 8–15 psi (55–105 kPa) is tolerated by the thorax of people in their fifties and sixties. The findings in this study regarding suitable stiffness of a side airbag correspond to the research data for the elderly people.

The force–deflection characteristics of a ventilated side airbag changes with the impact speed (figure 12). The bag gets stiffer with increasing impact velocities. This is needed for a system that shall improve the protection during less severe to more severe side impacts with door intrusion.

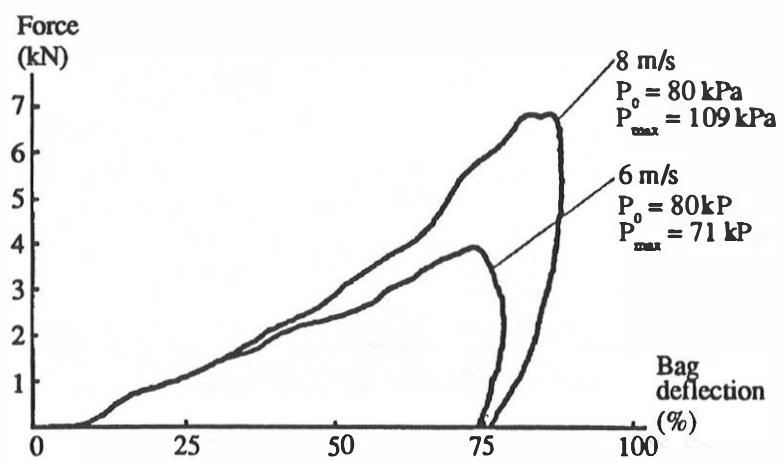

Figure 12. Force – deflection characteristics of a 12 litre ventilated side airbag at two impact speeds.

In order to estimate the ventilation area and the initial bag pressure that will result in the lowest chest deflection and the lowest chest VC a mathematical BioSid model was used. The model was developed in the crash victim simulation software MADYMO (TNO, 1992). The matematical BioSid dummy is a 2-dimensional lumped mass model (Pipkorn, 1992) and consists of eight body parts; the head, neck, shoulder, thoracic rib, abdominal rib, spine, pelvis and legs. The spine and the ribs are connected by a number of springs and dampers. The pelvis flesh is modelled by a separate mass. The model was validated by comparing predictions of the model with results form pendulum as well as sled tests.

To obtain the force-deflection properties of the airbag at different initial bag pressures and ventilation areas a mathematical model of mechanical drop tests (figure 10) was developed (Pipkorn, 1993). The contact area and the effective bag penetration volume was estimated from the tests. The mass flow out of the bag, due to ventilation, and the bag pressure during the penetration phase was calculated. The contact force was obtained by multiplying the airbag pressure with the contact area. The model was validated against a number of drop tests at 12 m/s and 10 m/s impact speeds.

The mathematical model of the 12 litre airbag and the model of the BioSid dummy were then used to estimate the chest deflection and the chest VC at door velocity histories corresponding to the sled test conditions. The results at 12 m/s door impact velocity, 0, 40 and 80 kPa initial bag (over) pressures and for ventilation areas up to 4 times the maximum possible in the sled tests (1500mm^2) can be found in figure 13 and 14.

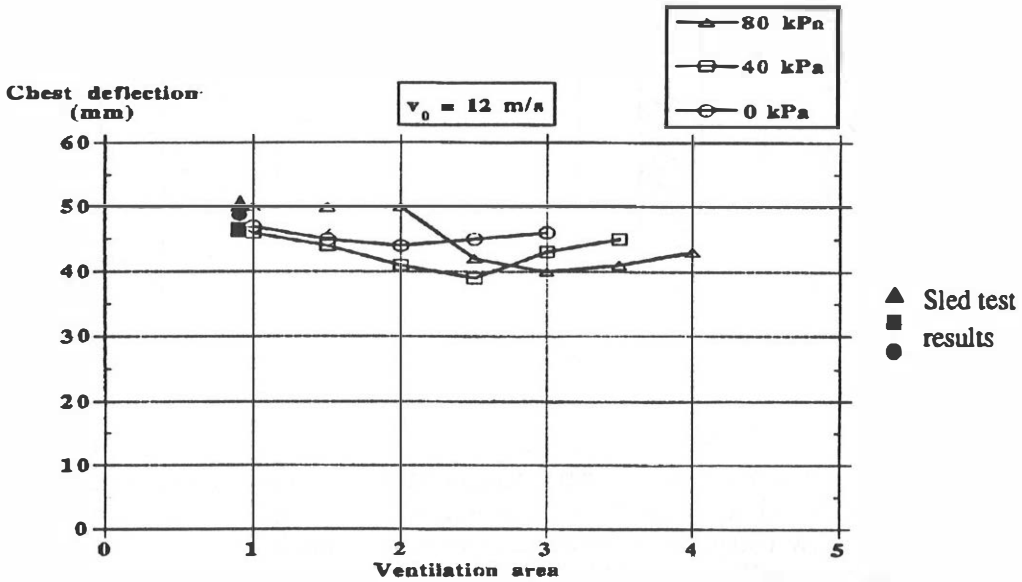

Figure 13. Chest deflection versus ventilation area and initial bag pressure according to mathematical simulations. (Ventilation area 1 = 1500 mm^2).

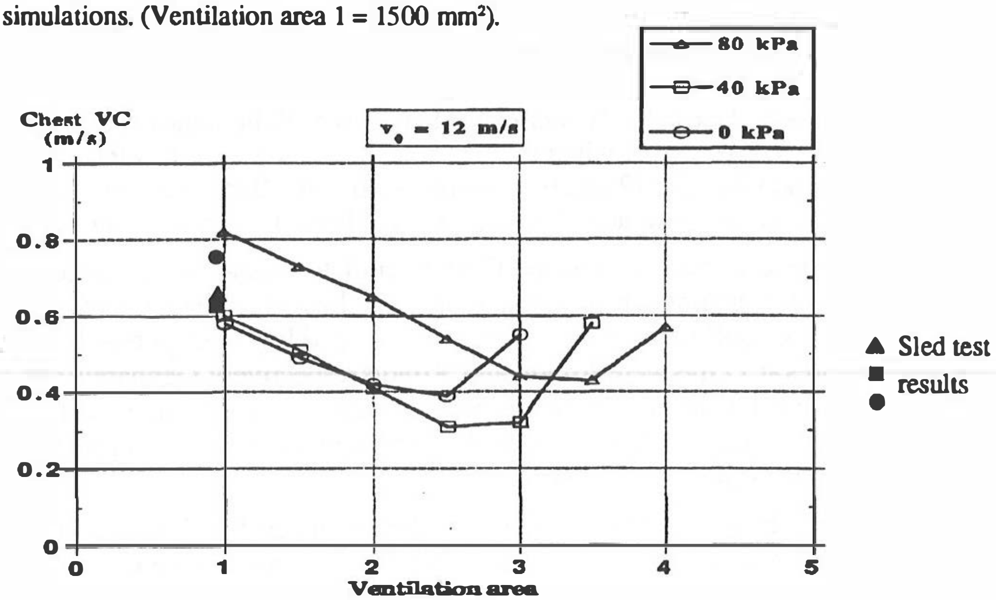

Figure 14. Chest VC versus ventilation area and initial bag pressure according to mathematical simulations. (Ventilation area 1 = 1500 mm^2).

The lowest chest deflection, 39 mm, and the lowest chest VC, 0.3 m/s, was reached at an initial bag (over)pressure of 40 kPa and at a ventilation area of about 2.5 times larger than the maximum area in the sled tests. It can also be seen from the curves that the minimum points for chest deflection and VC move towards larger ventilation areas as the initial gas pressure increases. For the 10 m/s door impact velocity the optimum bag pressure was somewhat lower and the optimum ventilation area was somewhat larger than for the 12 m/s door impact velocity.

This study has focused on deflection based chest criteria. The new American regulation for side impact protection, FMVSS 214, stipulates the acceleration based criterion TTI for the chest. This shall be below 85 g. Figure 15 shows a comparision of the TTI-figures between the 12 litre side airbag (40 kPa, 1/1 ventilation area) and the 50 mm chest padding (Ethafoam 220) configuration. The pelvic acceleration can also be seen. 75 mm of Ethafoam 220 padding was used in both configurations for the pelvic/thigh area. The FMVSS 214 criterion level is 130 g.

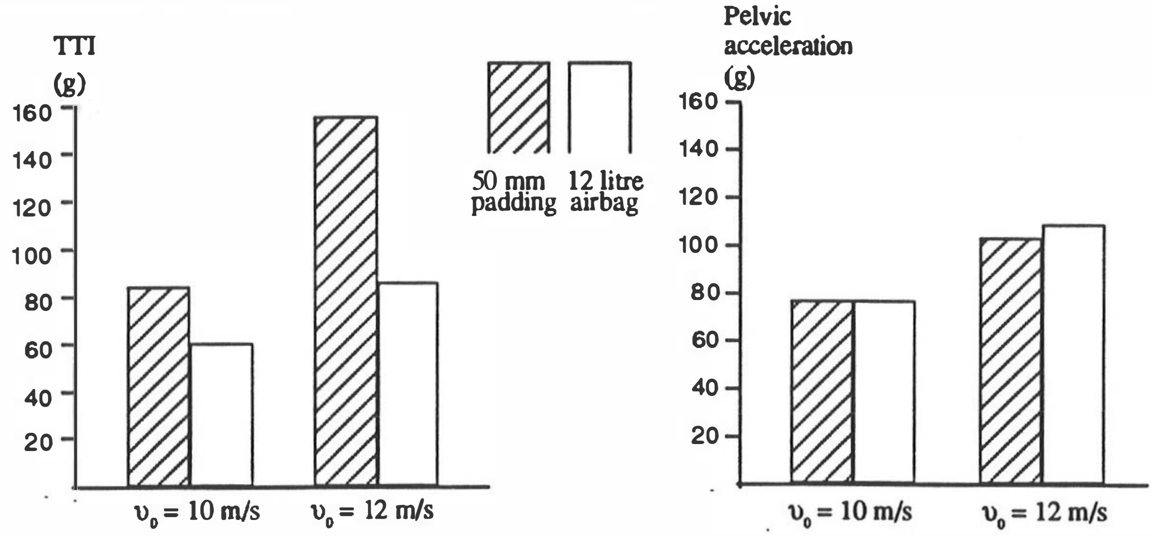

Figure 15. TTI and pelvic acceleration for the 50 mm chest padding and the 12 litre ventilated airbag configurations (N=1). 75 mm pelvic padding in both configurations.

The TTI was 30% lower for the airbag compared with the padding at the 10 m/s tests and 45% lower at the 12 m/s tests. The airbag is thus capable of reducing both deflection and acceleration based chest criteria. The 75 mm of pelvic padding was sufficient at both test speeds to keep the maximum pelvic acceleration well below 130 g. The peak pubic force was well below the European requirement (less than 10 kN). It was typically below 4 kN.

The bag also improves the protection for the head since it reduces the lateral displacement relative to the side window. Many of the life threatening head injuries are caused by head impacts to external objects, for example to the front of a van or a truck. Such an external object has been simulated in some tests by placing a 2 mm thick steel plate at the outside of the vertical side window frame (see figure 4). No head impact took place in the 10 m/s tests. There was a slight impact in the 12 m/s tests. Typical HIC values of 200 were recorded when the bag initial pressure was 40 kPa and higher. The HIC increased to above 400 when the 12 litre bag was replaced with 50 mm chest padding. However, if the bag (over) pressure was very low, at 0 kPa, there was no difference between the bag and the padding.

The rotation of the head was reduced by the 12 litre ventilated airbag (40 kPa) compared with the 50 mm chest padding. The maximum head to torso angular velocity (evaluated from high speed film) was 16 rad/s for the airbag configuration and 33 rad/s for the padding configuration at 10 m/s tests. The corresponding figures at 12 m/s were 26 rad/s and 50 rad/s respectively. Gennarelli and Thibault (1989) indicate a tolerance level of 30-40 rad/s for the head angular velocity in frontal rotation. If these values are used also for head lateral rotation, the side airbag configuration is acceptable. However, the chest padding configuration could be questioned.

Cavanagh et al. (1993) have found a shoulder force tolerance level of 3.5 kN for a 50 th percentile male. 2.5 kN was measured for the 12 litre side airbag (40 kPa, 1/1 ventilation area) in the 12 m/s test. The corresponding figure for the 50 mm chest padding configuration was higher, at 3.5 kN, close to the tolerance level.

The remaining body segment that is of concern in a side impact is the neck. In an ISO document (1984) an injury assessment value of 57 Nm have been proposed for the neck extension moment and 190 Nm for the neck flexion moment. The maximum neck moment was about 150 Nm for the 12 litre side airbag configuration, while it was almost 200 Nm for the 50 mm chest padding configuration. A major step to improve the protection of the neck can probably not be taken without introducing one more airbag or something else that stops the lateral rotation of the head at an early stage of a side collision.

Summary

The study has shown the effect of initial bag pressure and bag ventilation on deflection based injury criteria for a side airbag system at two different impact severities. The bag covered the chest and the abdomen down to the arm rest level. The volume was 12 litres.

It was found that the ventilation of the bag reduced the maximum chest deflection by 30 % and the maximum chest viscous criterion, VC, by 50% (comparison was made with the same bag without ventilation). A further improvement is possible for an optimum system. A suitable initial bag (over)pressure was found to be about 40 kPa, when also the loading of the abdomen was taken into consideration.

The chest deflection seems to be proportional to the door average velocity, during the first 20 m/s of deflection, to the power of about 2. The viscous criterion, VC, seems to be proportional to the same velocity to the power of about 4.

It was also found that a 12 litre ventilated side airbag resulted in 30–40% lower chest deflection and about 60 % lower VC than 50 mm chest padding (Ethafoam 220).

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