A STUDY ON THE BENEFITS OF DUAL-STAGE INFLATORS UNDER OUT-OF-POSITION CONDITIONS

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ABSTRACT

Fifty-three static out-of-position tests were conducted with a "small female" dummy placed in three different positions, and with distances of 0 mm and 50 mm from the airbag.

The driver-side module with a single-stage inflator was additionally tested with inflator versions tailored to 80%, 60%, 40% and 20% of peak tank pressure, in order to simulate the first of two stages of a dual-stage inflator.

In general, biomechanical loadings decreased with less inflator propellant. Critical chest loadings were measured down to the 60%-stage. The neck extension bending moment exceeded the limit only with the 100%-charge. With distances of 50 mm, none of the threshold values were exceeded. Charge reductions of 20% between two stages did not necessarily reduce occupant loadings.

DURING RECENT YEARS, a number of cases from the accident field have been reported in which airbags accounted for severe or even fatal injuries in low-speed crashes. The occupants affected were mostly small-statured drivers or children riding in the passenger seat who were "out-of-position" (OoP) at the moment of deployment initiation. Although most of them were found unbelted or otherwise improperly restrained, these occurences have led to the rapid introduction of a "depowering" option for airbags by NHTSA (1997) as a temporary measure until September 2001. While diminuition of the inflator energy is considered to reduce airbag aggressiveness in OoP, its protective effect in severe crashes decreases as well. For this reason, the FMVSS 208 "unbelted" requirement has been revised for depowered systems. For the future, the introduction of "smart airbags" is demanded, since these are expected to provide variable inflator output for "out-of-position" and "in-position" situations.

Potential future applications of these systems are seen in tailoring of restraint system performance to other parameters such as impact velocity and occupant size under "in-position" conditions. These systems, however, require extensive and reliable input by sensors and electronics to detect crash conditions and to initiate the necessary adjustments in the system. While detailed definitions of "smart" features and performance are still under discussion, dual-stage inflators are widely considered to represent a major component of a "smart restraint system".

Dual-stage inflators have two separate chambers for solid propellant or compressed gas. They can generally be ignited separately, with a time delay, or simultaneously, and are thereby capable of producing different pressure-vs.-time histories. Depending on the ratio between the two chambers, these inflators are designated generally "X% / Y%" dual-stage inflators. "X% / Y%" combinations actually implemented range from "50% / 50%" up to "80% / 20%". The particular partition depends on the philosophy pursued in lay-out design of the airbag system.

Nevertheless, decisions on the inflator design – and therefore also on the partition of a dual-stage inflator – are necessary in an early development phase of a restraint system. Such decisions determine its tailorability in the following development process, whether for use under in-position or out-of-position conditions. The objective of the present study is therefore to provide basic information on the influence of the stages of different energy levels on biomechanical loadings under out-of-position conditions. The ultimate purpose is, in turn, to facilitate decisions on inflator design for particular applications.

SCOPE OF RESEARCH PROGRAM

Although the results of depowering have been examined and discussed extensively, these measures are restricted to conventional airbag systems incorporating single-stage inflators. Broad knowledge accordingly exists only on the effect of inflator energy reductions by 20% to 35% (NHTSA, 1997; Prasad, 1996). Prognosis of the benefits of even greater inflator charge reductions on out-of-position occupants has proved difficult, since test results are few in number and numerical simulation based on multi-body systems does not yield reliable results for occupants in very close proximity to the airbag.

The objective of the present study is therefore to provide basic information from experiments on the influence of the stages of different peak pressure levels on occupant loadings under static OoP conditions as defined by ISO (1996) and SAE (1990). Low-charged stages of 20% to 60% are of special interest here, because these can be assumed to be fired primarily in cases of a clearly detected OoP scenario. In order to keep the number of involved design parameters small, the program described here focuses at present on driver-side airbags. For investigation of passenger-side airbags, it would be necessary to consider a wider range of bag volumes and shapes, module locations, and relevant occupant sizes.

TEST SETUP

The test mock-up especially used for this study consists of two main components: an adjustable seat for accommodation of the dummy, and a test rig to support the steering wheel and the driver-side airbag module. The steering wheel and the airbag module can be adjusted horizontally and vertically, as well as in their angular position.

The steering wheel used here is made from steel tubing and simulates the shape of a four-spoke wheel. The airbag module is connected to the base mounting plate by three load cells to allow assessment of forces in the axial direction of the steering wheel.

DUMMY

A "small female Hybrid III" dummy with standard instrumentation, additionally equipped with a tri-axial upper neck load cell, served as anthropomorphic test device. In order to ensure enhanced biofidelity for neck and chin geometry, the dummy was fitted with a neckskin and a chin insert. These were prepared in close conformity to the parts described by Melvin et al (1993). Care was taken not to alter the force-deformation behavior of the neck and head area by these measures.

AIRBAG MODULE

For the study, a baseline driver-side airbag module was chosen which featured state-of-the-art design, and which was representative for a great number of currently used airbags.

All tests took place with a driver-side airbag module, with an uncoated 60-liter cushion folded according to the P-folding technique. This folding pattern has proven beneficial under OoP conditions, especially with regard to neck loadings (Adomeit, 1995; Malczyk 1995), and has become a standard feature in the airbag modules of various car manufacturers. The module cover in dual-component plastic features a horizontal split line which produces two doors of approximately the same size.

The airbag module additionally incorporates a diffuser made from sheet metal stamping which covers the inflator and secures the bag to the module housing. This part ensures that only one layer of cushion fabric lies on top of the inflator, and at the same time keeps a small gap between the inflator outlets and the fabric to reduce thermal stress. For assessment of deployment pressure in the cushion, a measuring point was located in the center of the diffuser top.

INFLATOR

Generally, dual-stage inflators are designated by the prefix "X% / Y%": e.g., "80% / 20%"-dual-stage inflator. X% and Y% stand for the size of the respective inflator stage and sum to "100%" for the entire inflator. Different definitions, however, are in use for this designation among inflator manufacturers:

For example, "X%" for one of the two stages may be defined as:

a) Providing X% of the total (i.e., 100%) space for propellant inside the respective inflator chamber
b) Providing X% of the total mass of propellant in the respective inflator chamber
c) Delivering X% of the maximum tank pressure that a 100%-reference inflator develops in a tank test: i.e., a 60-liter tank for driver-side inflators.

It is obvious that definitions a) and b) do not explicitly describe the performance and peak pressure of an X%-stage of an inflator, and that they leave room for divergence; e.g., through variation of pellet sizes and shapes.

It is important to note that distribution of a given amount of propellant into two separate chambers, even if fired simultaneously, will not achieve the same pressure level as one coherent charge of the same total size.

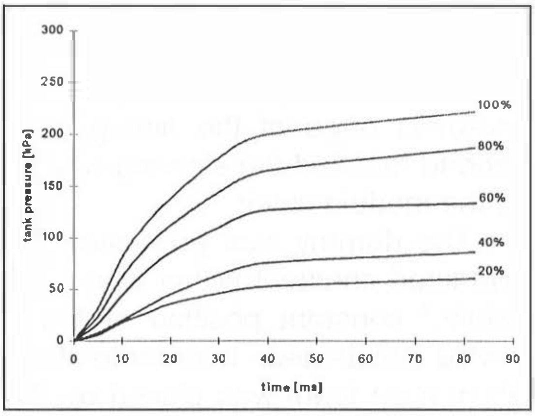
Even definition c), which incorporates the maximum pressure at a given point in time, fails to allow for precise description of the characteristics of the pressure curve as a function of time. Earlier studies indicate that the rise rate of tank pressure appears to better characterize the aggressiveness of an inflator for the "chest against module" OoP configuration (Prasad, 1996; Nusholtz, 1998). These approaches propose both peak pressure and maximum rise rate as key figures for specification. Prasad et al. (1996) have proposed supplementing this characterization by application of their so-called thrust variable, for which they found a correlation with V*C loading of the dummy's chest.

The driver-side inflators used for this study are based on a series-production type for 64 liters which employs solid non-azide propellant. Owing to the fact that dual-stage designs were not available in all of the different partitions scheduled for the test program, only one of two stages was simulated by a partially charged single-stage inflator. It may confidently be assumed that only this stage itself would be fired in an OoP situation, in order to achieve as little energy input on the occupant as possible.

Single-stage inflators with peak tank pressure levels of 20%, 40%, 60%, and 80% were prepared, compared to the known 100%-reference inflator from series-production, applying the maximum tank pressure criterion according to definition c). Since the series-production inflator housing was used for all versions in this study, it was necessary to fill excess room in the combustion chamber with inert material depending on the amount of propellant used. Several pre-tests were conducted in 60-liter tanks in order to tune the inflator charge to the desired tank pressure levels. Documentation took place in the form of mass-flow calculations and pressure measurements. Results from real tank tests given in Fig. 1 include peak tank pressure, maximum pressure rise rate and the rise rate at 10 ms. The final key figure was added in order to allow comparison of inflator behavior at the point in time at which the majority of V*C maxima occurred in the tests.

Fig. 1 – Tank pressure curves and rise rates of inflator versions (in 60-liter tank)

Inflator Peak Tank Pressure	Max. Pressure Rise Rate [kPa / ms]	Pressure Rise Rate at 10 ms [kPa / ms]
20%	2.26	2.16
40%	2.64	2.54
60%	5.68	5.66
80%	6.64	6.54
100%	8.88	8.1



METHODOLOGY

For effective study of fundamental effects with airbags of different energy levels, as well as analysis of their interaction with OoP, it was decided to conduct static tests. Restricting the setup to the above-described test mock-up reduces the number of influencing factors to only a few parameters. Whereas the rigidity of the steering wheel simulation and module mount entail more severe conditions in terms of energy absorption, the static test setup lacks the influence of vehicle deceleration present in a dynamic test environment. Prasad et al. (1996) have pointed out that tests under dynamic conditions may produce loading values up to twice those measured in static tests.

The test matrix with variation of dummy positions and distances is oriented to a previous study performed to compare the influence of different bag-folding patterns under OoP conditions (Malczyk, 1995). In accordance with ISO "Technical Report" (1996) for the assessment of OoP performance of airbags, tests took place for "chest centered on module" and "chin on top of module", supplemented by the configuration "forehead centered on module" included in earlier ISO issues (Fig. 2). Contrary to the above-mentioned study which examined distances of 0 mm, 20 mm, 50 mm, and 100 mm, only the "against" (0 mm) and 50-mm conditions were tested here. Testing for all the parameter combinations with dummy posture and distance from module took place separately, with inflators simulating the 20%, 40%, 60%, and 80%-stage; as well as with the baseline module incorporating the 100%-reference charge.

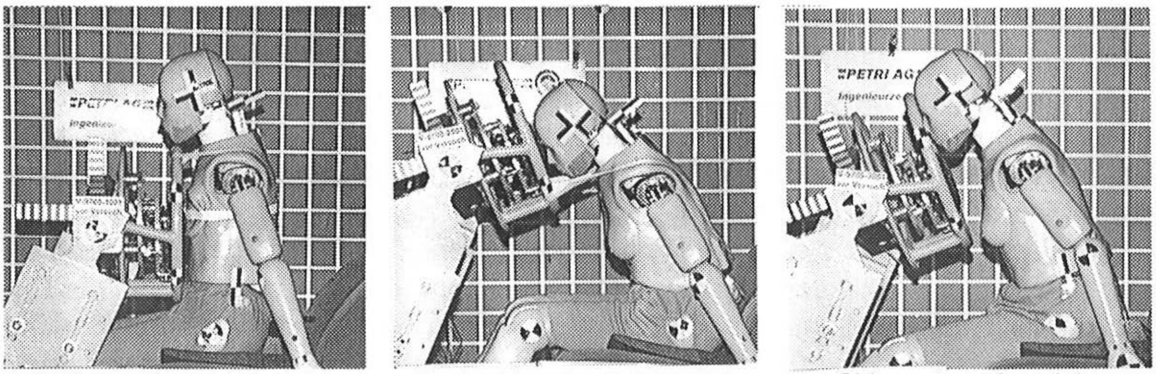
In order to reduce the effects of random parameter deviations on results, each test was conducted twice (with the exception of the 20%-stage with 50 mm separation and a number of "chin on top of module" tests with 50 mm distance, after the 0-mm condition had already resulted in very low loadings).

CONDUCT OF TESTING

For the tests "chest centered on the module," the axis of the steering wheel and the air bag module were horizontally positioned to pass through the center of the dummy's rib cage. For orientation of the forehead centered on the module, the steering wheel was inclined by 20 degrees to allow the head to be placed against the module. The axis passing 25 mm above the c.g. of the head was aligned with the center of the module. The "chin on module" posture was achieved by positioning the dummy's thorax parallel to the inclined steering wheel, with the tip of its chin coinciding with the horizontal line through the uppermost edge of the airbag cover. In the 0-mm position, the dummy's forehead touched the steering wheel rim, leaving a small gap between the chin and the module cover.

The dummy was positioned on the seat, with the height of the H-point maintained constant within all configurations. With "forehead centered on the module," constant position of the H-point in the longitudinal direction was likewise maintained. In order to stabilize the dummy position on the soft seat, a slab of hard foam was placed on the seating surface. In order to ensure the correct position in front of the module, it was in some cases necessary to secure the dummy at its shoulders by attaching easily-tearing adhesive paper tape to the steering wheel rim. In order to achieve as small a dummy-module separation as possible for the configuration "chest centered on the module" it was necessary in these tests to tie down the breasts of the small female with adhesive tape. Film documentation took place with two high-speed video systems (4,500 images/s) and a high-speed film camera (1,000 frames/s).

Fig. 2 – Dummy out-of-position configurations for a distance of 0 mm


Chest centered on module Forehead centered on module Chin on top of module

TEST RESULTS

For evaluation of occupant loading, scaled Injury Assessment Reference Values (IARV) for the small female Hybrid III (Melvin, 1993; Mertz, 1993) were applied. The Viscous Criterion (V*C) values were calculated according to the formula presented by Mertz (1993). Bending moments measured with the tri-axial upper neck load cell were corrected to the plane through the head-neck joint.

CHEST CENTERED ON MODULE

Chest loading – For both distances from the module, sternum deflection demonstrates an immediate rise, becoming steeper with increasing inflator charge. This loading is attributable to the punch-out mechanism (Horsch, 1990) and coincides with occurrence of the V*C maximum. V*C maxima occurred within a time frame between 8 ms (100%-stage) and 16 ms (20%-stage) after deployment initiation, with the majority of maxima concentrated around 10 ms. For this reason, the respective pressure rise rates as indicators for inflator energy were calculated at 10 ms to allow comparison among the versions. Great increases in maximum rise rate resulted between 40% and 60%, and between 80% and 100%. These values coincide with sternum deflection and V*C increases in the respective tests. The latter exceeded the limit of 1.0 m/s with the 60%, 80%, and 100%-stages with "chest against module".

In contrast to the above, the position 50 mm from the module resulted not only in halving of thorax loadings, with values remaining safely below the thresholds, but also in revealing different deployment behavior of the bag.

Corresponding to the findings of the previous OoP study (Malczyk, 1995), these results may be explained with the general character of the P-folding pattern of the bag. When it is obstructed by an OoP occupant during deployment, the bag unfolds radially under the condition that there is at least a small gap between the module cover and the dummy's body. It is only when the chest initially contacts the module that exclusively the gas forces of the deploying airbag act directly on the occupant.

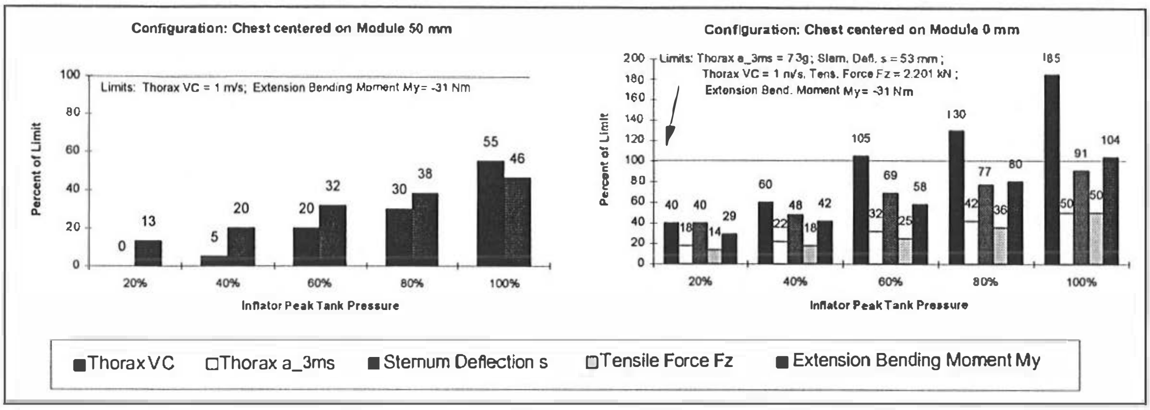
The dummy thorax delayed the module doors from flipping open throughout the test configuration, whereas the upper door did not flip open with 20% and 40%-charges. This caused a smaller bag volume to escape from the module, since part of the fabric remained folded in the module. Consequently, the peak pressures in the bag were up to 50% higher than those found with a dummy/module distance of 50 mm.

Neck loading – For the neck, extension bending moment was the critical form of loading. Again, the values remained clearly below the limit of -31 Nm for the small female positioned 50 mm away from the module but exceeded the threshold at a separation of 0 mm in combination with the 100%-inflator stage. Both extension bending moment and axial tensile force increased with higher inflator charges. Their maxima occurred during the first 15 ms after airbag triggering, still without contact between the deploying bag and the dummy head. These loadings may therefore be explained as coupling forces introduced by the chest being accelerated rearwards and the head remaining motionless due to its inertia. Unlike most situations in which critical neck loads are encountered due to membrane loading through the cushion, the cause in this case for these injury mechanisms must be attributed to the punch-out effect.

The other neck loading types remained noncritical in all tests with "chest centered on module". Flexion bending moment demonstrated a slight upward tendency with increasing inflator energy.

Head loading – Head accelerations were low, with 3-ms values reaching a maximum of 22 g in the "against module" configuration.

Fig.3 – Critical loadings for configuration "chest centered on module"



FOREHEAD CENTERED ON MODULE

Chest loading – As could be expected, loadings of the thorax were very low due to its distance from the airbag. With 50 mm separation of the forehead from the module and charges lower than 60%, the bag did not contact the chest at all because only a partial portion of the bag was extracted from the module. Only thorax acceleration (3-ms value) reached an appreciable maximum (15 g) with the 100%-reference inflator and with the forehead resting against the cover. At the same time, sternum deflection and V*C values were negligible.

Neck loading – For both distances from the module, neck bending moments represent the major injury risk. A clear difference between the two configurations, however, is apparent. When the forehead initially contacts the module, both flexion and extension are the dominating loadings, with the baseline module reaching 70% and 62% of the scaled IARVs for flexion and extension. Flexion is introduced through punch-out loading of the head during the first milliseconds, whereas extension builds up considerably later when the cushion has achieved its full radial extent in front of the forehead. This extension phenomenon must therefore be attributed to the membrane loading effect.

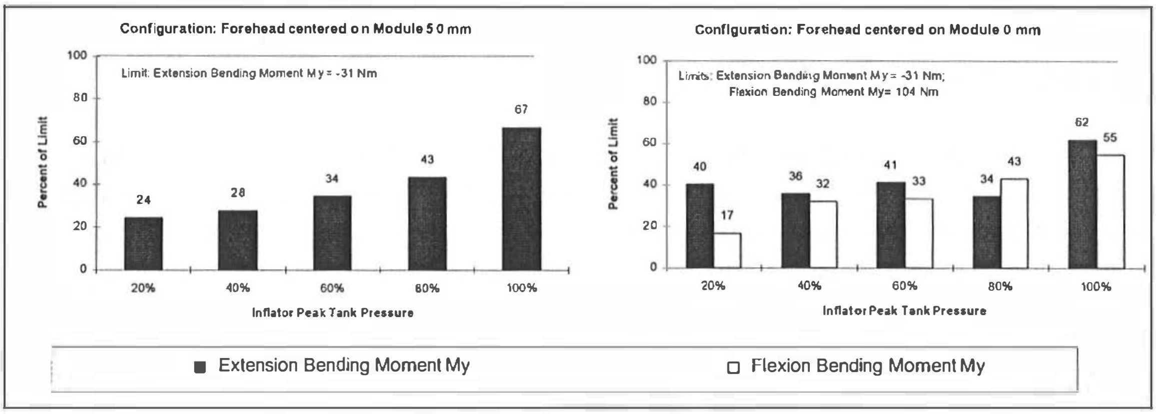
In this configuration, shear force and compression force in the neck reached their maximum values throughout the entire study. With 44% and 32%, however, they remained safely below their respective limits.

At a distance of 50 mm from the module, the situation fundamentally changes. All neck injury criteria are uncritical, but extension bending moment almost doubles in the step from 80% to 100% of inflator peak pressure, and reaches 67% of its threshold value. This results in greater loading than in the 0 mm configuration. Film analysis reveals that the bag inflates almost entirely in front of the dummy's face with 50-mm separation. With direct contact on the cover it also spreads towards the thorax and distributes the loads on chest and head more equally.

Whereas neck loadings increased with higher-charged inflators throughout the range of peak pressure levels investigated, this phenomenon did not appear in general in the extension bending moment with the forehead against the module. Here, the 60%, 40%, and 20%-stages produce slightly higher extension values than those found with the 80%-stage. This may be explained by the fact that the bag did not deploy completely from the module with lower charges, but that it developed considerable pressure acting on the head. With the 80%-stage, the airbag unfolded completely in front of the chest as well which led to almost simultaneous rearward acceleration of the head and thorax. Further increase of the charge to 100% filled the bag tautly, which nearly doubled the maximum extension moment.

Head loading – Despite the position "forehead against module," the 3-ms values did not exceed 30 g; HIC values were negligibly low.

Fig. 4 – Critical loadings for configuration "forehead centered on module"



CHIN ON TOP OF MODULE

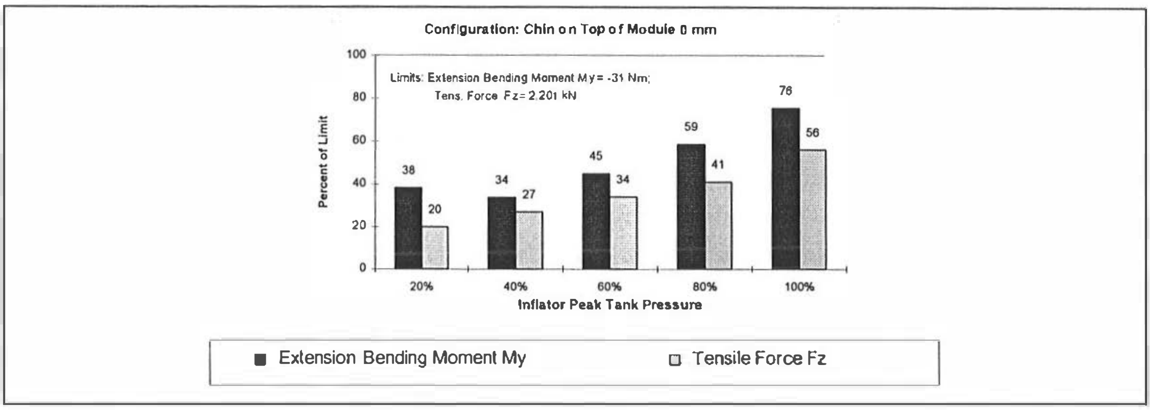
Chest loading – All thorax injury criteria remained noncritical throughout this test configuration, the highest relative loading type being sternum deflection. Nevertheless, the maximum for sternum deflection reached 20 mm with the baseline airbag remaining far below the threshold of 53 mm for the small female.

Neck loading – General increase in neck loadings becomes visible when the energy level of the airbag inflator rises. At a distance of 0 mm, neck extension is the major loading form, with maximum values of 23.4 Nm, compared with the limit of -31 Nm. Axial tensile forces range from 20% to 56% of the respective limit. Whereas flexion values are very low at 0 mm, they reach 40% of the respective IARV with 50 mm. The extension values for this distance also reach 40% of IARV.

Head loading – The highest 3-ms values were below 18 g, and HIC-36 maxima were 35.

All of the biomechanical loadings in the configuration "chin on top of module, 0 mm" were below their IARVs. Furthermore, the results for the 80% and 100%-stage and 50 mm confirmed this trend. Consequently, it was assumed that the remaining combinations with 20%, 40%, and 60%, at 50-mm distance, would produce small loading values, and they were dropped from the test matrix.

Fig. 5 – Critical loadings for configuration "chin on top of module"



SUMMARY AND CONCLUSIONS

In the present study, comparative static out-of-position (OoP) tests were conducted with driver-side airbags. The objective was to obtain information on the influence of dual-stage inflators with partitioned charges on the biomechanical loadings of an OoP occupant. Various amounts of solid non-azide propellant tailored during previous tank tests simulated the first of two inflator stages to be fired alone in case of a detected OoP situation. Peak tank pressure levels of the inflator versions ranged throughout 20%, 40%, 60%, and 80%, with percent reference to a series-production module.

The experiments were conducted on a rigid test mock-up representing the environment for the airbag and the driver. A "small female Hybrid III" dummy, additionally equipped with an upper neck load cell and neckskin, was used for assessment of injury-relevant loadings.

Testing comprised three main configurations: "chest centered on module," "forehead centered on module," and "chin on top of module," according to ISO recommendations. In addition to positioning the respective body region directly against the airbag module (distance of 0 mm), all configurations were also tested with a distance of 50 mm.

The configuration "chest centered on module" resulted in the highest biomechanical loadings in all tests conducted, both for the thorax and the neck. Biomechanical-loading results exceeded the V*C limit with 0-mm distance and inflator stages of 60%, 80%, and 100%, whereas sternum deflection remained closely below the threshold for the baseline module, and thorax acceleration remained noncritical for all energy levels.

Neck extension bending moment slightly exceeded limits for the 100%-reference inflator and for the configuration of the chest against the module cover. In contrast to all other dummy/module configurations in which membrane loading by the inflating bag caused extension moments, the test results in this case must be attributed to the violent acceleration of the thorax.

With the "forehead centered on the module," only neck bending moments and tensile forces are of significance; none of these, however, exceeded the scaled IARVs. Direct positioning against the module cover resulted in both flexion and extension which represent the greatest loading in this case. At a distance of 50 mm, only extension remains relevant, due to changing bag deployment behavior under these conditions.

Whereas all loading values increased gradually as a result of higher inflator charge, this did not apply to extension moment when the forehead was placed against the module. Due to the fact that lower charges did not deploy the entire cushion from the module, and since forces therefore acted only on the head, the 20%, 40%, and 60%-stages produced higher bending moments than the 80%-stage. As in all other configurations tested, values for the head were noncritical with respect to the relevant head-injury criteria.

With the dummy's "chin on top of module," all biomechnical values likewise fell short of their respective limits. Here again, neck extension moment and tensile force delivered the relatively greatest loadings, generally rising with increasing inflator charge. Depending on the distance from the module and the resulting deployment behavior, either extension alone, or extension together with flexion, represented the dominant loading.

For all OoP configurations tested, a distance of 50 mm produced loadings which in all cases remained safely below threshold values for the small female. In view of an earlier study on the influence of bag folding patterns on OoP results, this result must be partially ascribed to the P-folding employed for the present airbag module. Under these conditions it appears that dual-stage inflators offer highest benefits for OoP drivers in the "chest against module" configuration. In this case, an 80%-charged inflator stage would suffice to observe the relevant neck extension limit, whereas a 20% or 40%-stage is required to remain below the limit for chest V*C. It is noteworthy, however, that – while the tested inflator versions were tailored to produce constant increases between "neighboring" peak tank pressures (i.e., energy levels) – this linearity was not present with their respective pressure rise rates (i.e., power levels) at the point of highest punch-out loading. Steep inclines occur especially between 40% and 60% and between 80% and 100%. Since reduction of V*C values can also be achieved through onset fine-adjustment of the propellant, and since a gap between module and chest is possible by means of a dished steering wheel, it can be assumed that relatively slight propellant reductions – in other words, inflator stages of 60% or 80% – are realistic in order to meet all requirements for driver-side airbags under recommended ISO conditions.

Whereas reducing the inflator charge from 100% to 80% produced the best relative improvements in many cases (i.e., loading reduction with respect to inflator energy reduction), the 20%-stage did not enable significant advantages compared with the 40%-stage for the configurations "forehead centered on module" and "chin on top of module".

In view of recent discussion on the possible residual benefits of partially inflated airbags for restraint purposes, even under OoP conditions, the effects found during this study present an interesting option. As determined in tests with reduced amounts of propellant and in conjunction with the bag folding pattern, deployment of only a portion of the bag occurred – however, with considerable inflation pressure. Future concepts for adaptive airbag volume could well benefit from this design.

It must be emphasized that the objective of the present study was to provide results which are valid for a wide range of driver-side module designs. Nevertheless, significant deviations from the design presented, for instance by employing different inflator technology or radical relocation of the split line in the module cover, may also influence prospects for OoP results. This likewise applies to the situation on the passenger-side, at which the number of influencing parameters is even greater.

Future developments to reduce injury risk for OoP occupants, however, must not sacrifice the airbag performance which is needed to provide protection for vehicle occupants in severe accidents.

ACKNOWLEDGMENTS

The authors would like to thank Dynamit Nobel GmbH for their collaboration in preparation of this study.

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