Numerical Optimisation of a Seat Energy Absorber

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SUMMARY

Modern helicopter seats are equipped with an energy absorber to reduce lumbar spine load during crash landing. The corresponding FAR/JAR Standards request a dynamic test, with an anthropomorphic test dummy, to demonstrate the effectiveness of the system.
This paper describes the preliminary validation of the multi-body model of a new anthropomorphic test dummy and crashworthy helicopter seat, and the optimisation of its energy absorber under revised impact conditions, more severe than those requested by the regulations, but probably more appropriate with respect to the current helicopter accident envelops.
The classic approach to the problem brings to an absorber that, after a short elastic deformation, has a constant load response, which is the current solution. A numerical simulation steered by an optimiser, however, demonstrates that lower levels of spine loads, or lower strokes, can be reached if the absorber has a variable load-stroke response.
The research was conducted within the Helisafe European project, concluded in March 2003 within the 6TH Framework. The target of the project was the upgrade of cabin safety for civil helicopters, based on a revision of the dynamic test conditions, cabin delethalisation and improvement of crashworthy systems.

INTRODUCTION

Helicopters are the aircraft category with the most stringent requirements concerning crash landing, especially considering load conditions with significant vertical component. As a matter of fact, the subfloor structure in a helicopter is commonly limited in thickness, to the detriment of energy absorption capabilities. Important increase of accident safety is reached with the installation of crashworthy shock absorbers on the main landing gear, but this solution is mostly feasible on military helicopters with long fixed landing gear. Seats can then give high contribution to survivability.
Modern helicopters are commonly equipped with crashworthy seats: an example is shown in fig. 1; in this solution, the seat is constrained by sliding joints to vertical tracks anchored to the cabin floor; one or two energy absorbers contrast the movement of the seat along the tracks.

Fig. 1 – Crashworthy seat

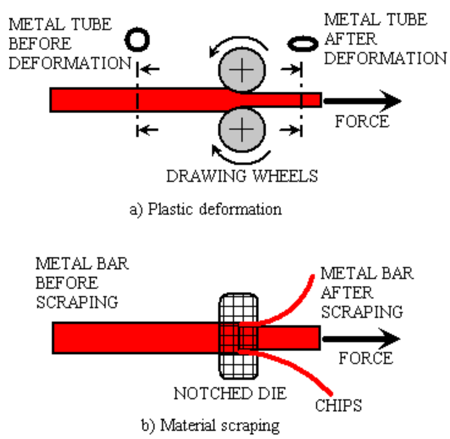


Fig. 2 – Techniques for seat energy absorbers

Commonly, an energy absorber is a constant load device, if one excludes an initial elastic part of the load-stroke curve. On helicopter seats, this behaviour is obtained by plastic deformation of a metal component or scraping of material. Fig. 2 shows examples of both techniques: in the first case, a metal tube with circular cross section is deformed when drawn through a pair of wheels; the force level is a function of the material properties, geometry and clearance between wheels; in the second case a metal bar is forced through a notched die and chips are scraped from the

surface of the bar; here the force level is function of the material properties, geometry and scraping depth.
Proper tuning of an energy absorber may require a considerable effort. The purpose of the absorber is to keep the lumbar spine load of the occupant below a tolerable limit, with the lowest possible stroke, during a severe landing with high vertical velocity. The effectiveness of a system is assessed by measuring the lumbar spine load during dynamic testing on the seat with anthropomorphic dummy. This procedure could also be used to develop the energy absorber design and tune it, but it is clearly expensive, both for the experimental equipment and because the seat is often deformed by the test loads and must be replaced in each test. Moreover, a simplified analysis of the problem may bring to very approximate results, mainly because the dynamic coupling between the anthropomorphic dummy and soft parts of the seat is highly non-linear.
For these reasons the numerical analysis of the problem is a more suitable support in the seat design and tuning. In particular a multi-body technique offers, in this case, the necessary detail in results and a very low computational time.

ORIGINAL AND REVISED TEST CONDITIONS

The dynamic test conditions with high vertical acceleration requested by FAR/JAR-27 and 29 [3 and 4] on helicopter seats are summarised in fig. 3. The seat is installed, with the anthropomorphic dummy, on the test sled in a 60° nose up attitude; acceleration is imposed to the sled in the direction indicated in fig. 3, with a peak of at least 30 g's, time to peak not greater than 31 ms and total change in velocity of at least 9.14 m/s.
The dummy is instrumented with an axial lumbar load cell; in fact the most restrictive certification criterion in this test condition is the lumbar spine load, which must be limited to 6.67 kN.
If one makes a very rough calculation and considers the corresponding linear dynamic load of the upper body of the dummy (33 kg, including arms and head, under 30 g's acceleration), this brings to 9.5 kN at the lumbar level; such a roughly estimated figure suggests that the system may need some form of attenuation.

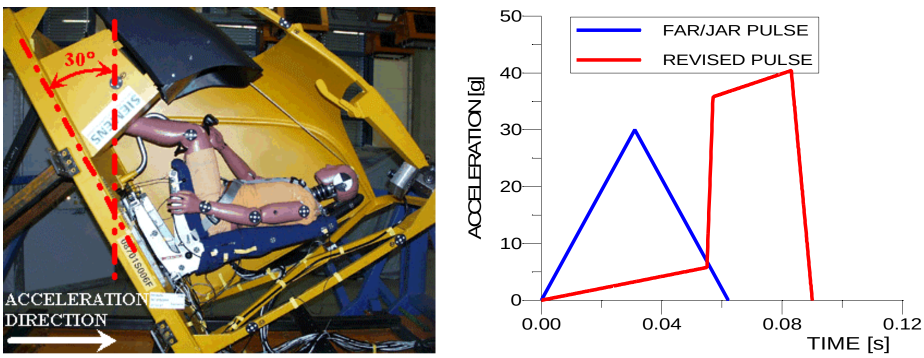


Fig. 3 – Test set-up (SIEMENS Laboratories), original and revised acceleration pulse

The revised cabin test conditions are also shown in fig. 3. They come from multi-body simulations on full helicopter structural models with an impact velocity of 12 m/s, carried out at DLR-Stuttgart with DRI/KRASH and at Politecnico of Milan with VEDYAC. The pulse starts with a low acceleration gradient for the first 55 ms, then increases rapidly to a level higher than the classic JAR/FAR pulse, and with a different shape. This condition represents an increase of more than 30% in velocity, or 70% in kinetic energy with respect to the JAR/FAR pulse.
Unfortunately, the revised test conditions could not be obtained by the dynamic equipments available at the Helisafe partners (Siemens Restraint Systems and Politecnico crash test laboratories at Alzenau and Milan respectively).

MODEL SET-UP AND VALIDATION

The optimisation of the seat energy absorber is here carried out with a multi-body simulation with VEDYAC, developed at the Department of Aerospace Engineering of Politecnico of Milan, Italy. It is a multi-purpose code, used in automotive and aerospace crashworthiness and includes some anthropomorphic test dummies in its database.
The first step towards optimisation of the seat energy absorption is the generation of validated models of both the dummy and the reference crashworthy seat.

The dummy used in Helisafe is an upgraded HYBRID III, with a modified lumbar spine for adaptation to FAR/JAR crashworthiness requirements [5]. The entire dummy and some body segments were tested at TNO Automotive (Netherlands) under different acceleration conditions; the tests were aimed at providing enough data for multi-body model set-up and validation [6]. In particular the entire dummy was tested under different acceleration conditions on a rigid seat, so that no influence of the seat elasticity was introduced in the body dynamics. The most significant conditions, here reported, correspond to the JAR/FAR test conditions for the seat and restraint system; one is specified in the previous paragraph; the other reproduces a longitudinal load condition of the aircraft: the seat must be installed, with the anthropomorphic dummy, on the test sled in a ±10° yaw angle (for the TNO test a 0° angle was actually chosen); an acceleration is imposed to the sled in the backward direction for the dummy, with peak of at least 18.4 g's, time to peak not greater than 71 ms and total change in velocity of at least 12.8 m/s.
The dummy model is a 17 rigid body system, representing main body segments, connected by joints, representing the articulations. Validation of this model required mainly the modification of some mechanical parameters and minor geometric changes. Mechanical changes were introduced in the lumbar spine axial stiffness, neck flexural stiffness and buttocks hardness. Geometric changes were simply the addition of contact possibilities between the chin and the thorax during high neck flexure.

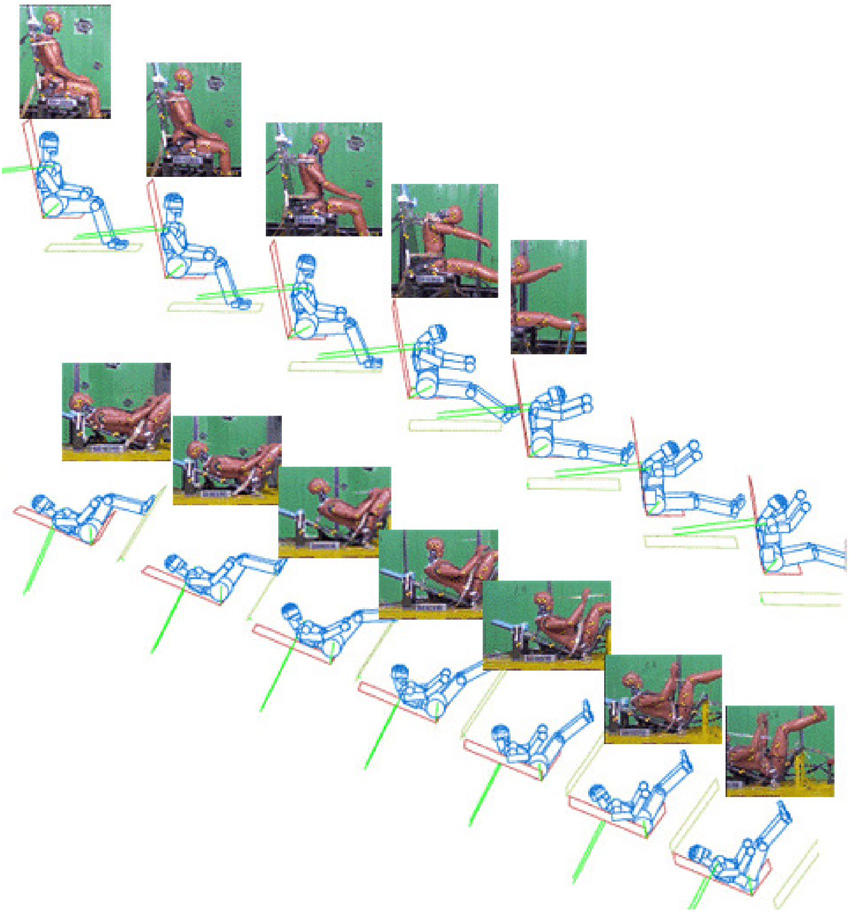


Fig. 4 – VEDYAC simulation of 0° and 60° TNO dynamic tests

Belts needed a consistent tuning. In this model they are simply represented by 4 cables, anchored to the seat system and connected to fixed nodes of the anthropomorphic dummy. This is the main limit of this multi-body solution, since any sliding of the belt on the body is not properly simulated. On the other hand this solution is very simple and could only be replaced by more complex systems, such as a chain of thin polyhedric bodies linked together, having low masses and high tensile stiffness, and therefore high eigenvalues: this usually implies a consistent integration time step reduction, and a consequent increase of simulation time.
The behaviour of the cable-like belt models is acceptable, provided that the belts are not significantly tensioned by movements of the dummy along the backrest plane, i.e. when the dummy moves vertically or laterally. For this reason, the anchoring points of the shoulder cables to the seat system are surprisingly far aft the seat: in this way, the cables will normally be tensioned by a forward movement of the dummy thorax, but will be slightly tensioned by a lateral or vertical movement, thus better representing a real belt behaviour.
Fig. 4 shows the graphic sequence of the simulation in both cases: front acceleration condition (0°) on the top strip, 60° acceleration condition on the bottom strip. Agreement of dummy positions is qualitatively satisfactory.

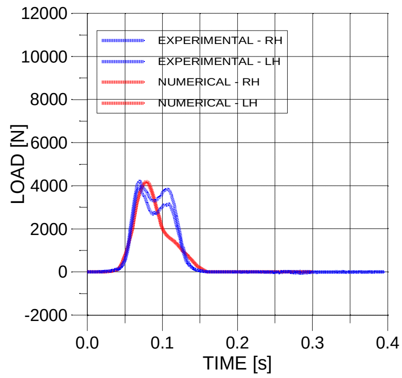


Fig. 5 – (0° case TNO) LH and RH shoulder belt loads

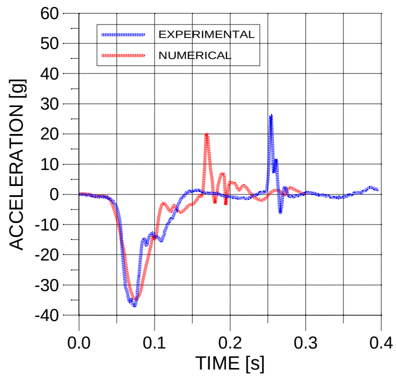


Fig. 6 – (0° case TNO) thorax front acceleration

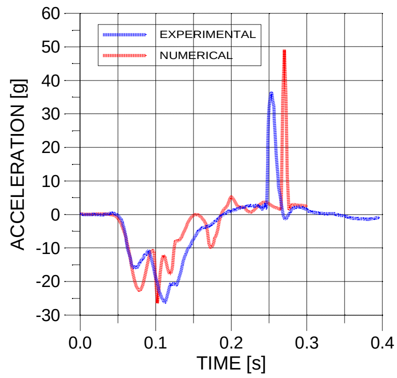


Fig. 7 – (0° case TNO) head front acceleration

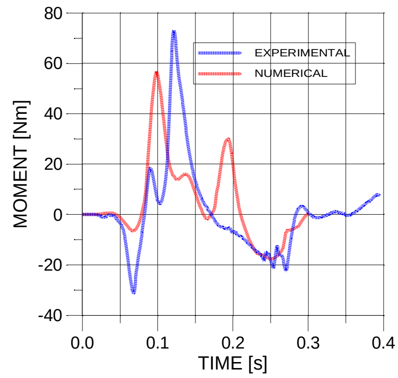


Fig. 8 – (0° case TNO) neck flexional moment

Fig. 5 to 8 show comparisons between a few numerical and experimental results, after final tuning of the model, for the 0° acceleration condition. The high peak in head acceleration after 250 ms is the head impact against the backrest.

Fig. 9 to 12 compare the results in the 60° case, which is more relevant to the subject focused by the present work.

The main results are in satisfactory agreement, with special regard to the lumbar spine load, which is the main objective function of the energy absorber optimisation, discussed later on. A lower biofidelity is observed in the neck behaviour, probably because the non-linearity and viscosity of the HYBRID III neck is not well reproduced by the numerical model of the cervical spine. Nevertheless this drawback should not have an important influence on the lumbar spine loading. Also in this case, the high peak in head acceleration after 200 ms is due to head impact against the backrest.

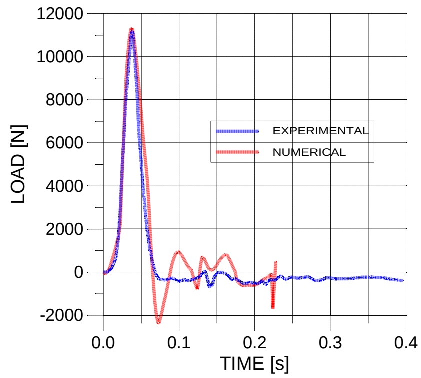


Fig. 9 – (60° case TNO) lumbar spine load

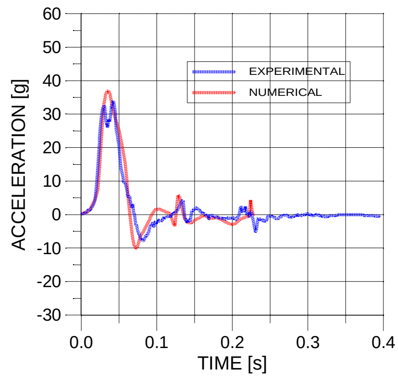


Fig. 10 – (60° case TNO) thorax spine-ward accel.

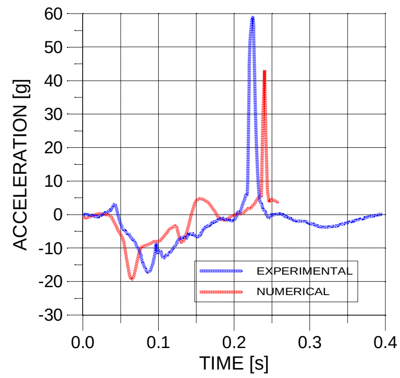


Fig. 11 – (60° case TNO) head front accel.

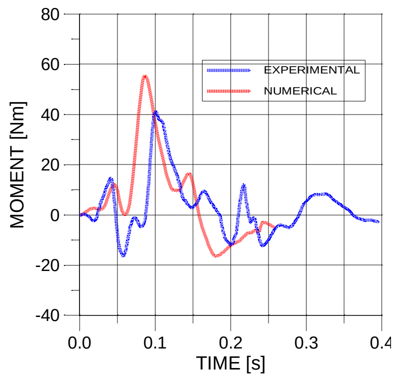


Fig. 12 – (60° case TNO) neck flexional moment

The second step is the validation of the seat model.

The seat is manufactured by Martin Baker and is of the type shown in fig. 1; it has a pair of energy absorbers between the seat body and the vertical supports.

A simplified two-rigid body model is set up as a first approach; in fact the 60° dynamic tests that were performed at Siemens and Politecnico with that seat did not show significant deformation of the seat and support structures, thus suggesting the possibility of a low detail model; one rigid body represents the seat moving equipment, the other represents the two supports. The seat moving body and the tracks are connected by 3 deformable joints: 2 of which are like translational joints and allow a free

movement of the body along the tracks; the third one represents the pair of two energy absorbers, i.e. is similar to the previous ones but develops a contrast load during the stroke. The two absorbers are thus modelled into one element with double stiffness and double constant load level. The body representing the tracks is connected to a massless floor with 4 joints, representing seat anchoring to ground. A suitable number of planes, or, better, plane facets, approximate the external geometry of the seat. The padded surfaces of the seat are modelled as relatively soft facets.
The model is validated against results of dynamic tests performed at Politecnico, in a 60° nose-up condition but with acceleration pulse not responding correctly to the JAR/FAR requirements. The tests were conducted with a complete mock-up of the helicopter cabin, including the front seat, for the evaluation of possible contact with the occupant. The graphic output in fig. 13 shows the simulation of the test.

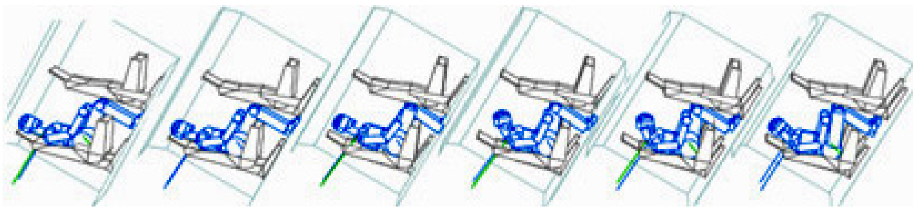


Fig. 13 – VEDYAC simulation of 60° dynamic test at Politecnico

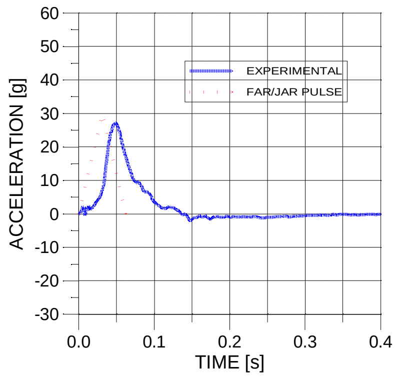


Fig. 14 – (60° case Poli) sled acceleration

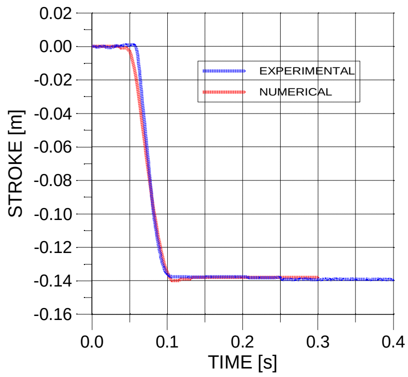


Fig. 15 – (60° case Poli) seat stroke

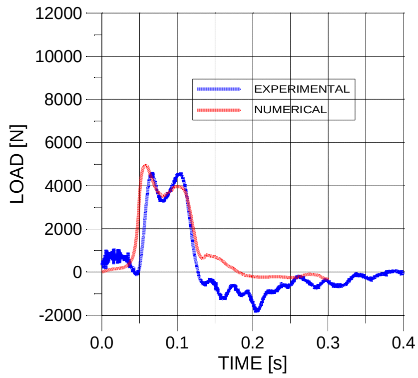


Fig. 16 – (60° case Poli) lumbar spine load

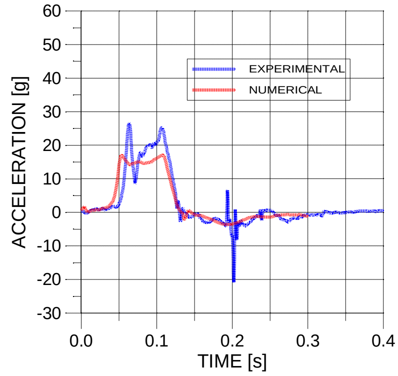


Fig. 17 – (60° case Poli) thorax spine-ward acceleration

Fig. 14 shows the sled acceleration generated at Politecnico and the one requested by FAR/JAR: the experimental pulse has a peak 10% lower than requested, but the corresponding velocity is 8% higher. Following fig. 15 to 17 show some comparisons between experimental and numerical results, also proving the effectiveness of the current seat energy absorber, which keeps the lumbar load lower than 4.6 kN.
The agreement is clearly satisfactory, especially as far as the lumbar spine load is concerned; satisfactory results are also obtained in the longitudinal acceleration condition, not reported in this article. The models of the dummy and crashworthy seat can thus be considered validated at this stage and usable for optimisation.

SEAT RESPONSE UNDER HIGHER ACCELERATION CONDITIONS

The model is now analysed under the revised acceleration conditions represented in the previous fig. 3, which is considered to be more representative for crash scenarios of modern helicopters. Optimisation of the seat energy absorbers will be performed under this condition.
The results of the new simulation under the revised acceleration condition, with the original energy absorber, shows that the seat runs the entire 200 mm stroke and bottoms out.This fact is clear from the seat energy absorber load history, because the bottoming effect in the VEDYAC model is actually obtained by a stiffening of the energy absorber, after travelling its allowable stroke. Of course this effect is transmitted to the occupant, resulting in a severe lumbar spine load peak.

These results are shown in fig. 18 and 19. The reader should remember that the seat model used here is simplified and that the energy absorber properties are condensed into one central deformable element, which of course has double mechanical properties with respect to the two real absorbers.

One must now consider that bottoming could be not properly modelled, since it is a combined effect due to contact loads, local and global seat stiffness. Bottoming is certainly a negative effect, and its severity is very sensitive to final stroke rate, but it is also a difficult event to evaluate accurately in a simplified model such as the one used at this stage. The plots reported in fig. 18 and 19 are actually clipped, i.e. the load peaks are higher than the full axis scale, but their real values should not be considered significant.

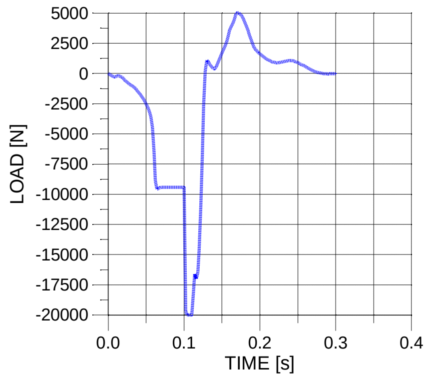


Fig. 19 – (60° case revised) Energy

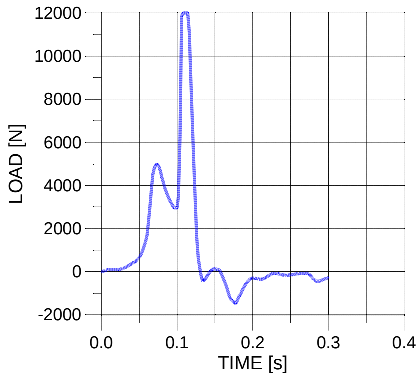


Fig. 19 – (60° case revised) Lumbar

Based on these considerations, we can say that:

1. the bottoming forces from the model might be not numerically correct;
2. bottoming should be always avoided to prevent high spine loads.

The optimal energy absorber allows an initial bottoming, but its tuning would be too difficult and the repeatability of test impact conditions is also not so high.

We can finally assume that the optimised energy absorber is the one that allows the lower lumbar spine load within the maximum stroke of 200 mm with no bottoming.

ENERGY ABSORBER OPTIMISATION

Two types of optimisation are considered, and the results are all summarised in fig. 20 and 21 together with the initial non optimised solution.

A first energy absorber optimisation is easily obtained by stiffening it for bottoming avoidance, but maintaining the elastic plastic behaviour. This is, of course, the easiest solution from the manufacturing point of view, since this only requires the re-sizing of a few mechanical components of the absorbing device.

This solution already brings to acceptable results in terms of ATD lumbar spine load, because it is reduced under the limit of 6670 N indicated by JAR/FAR. Actually, this success is marginal, because the lumbar load reaches 6400 N.

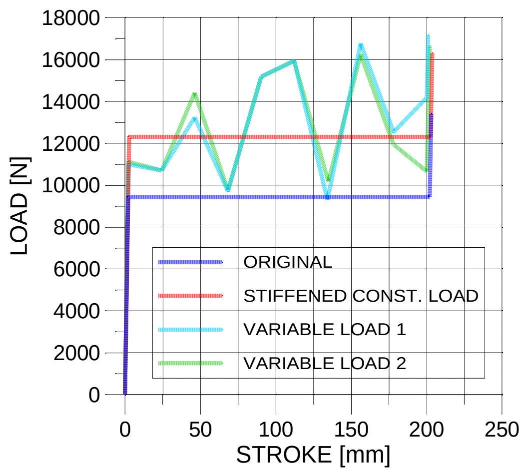


Fig. 20 – Energy absorber load profiles (dynamic)

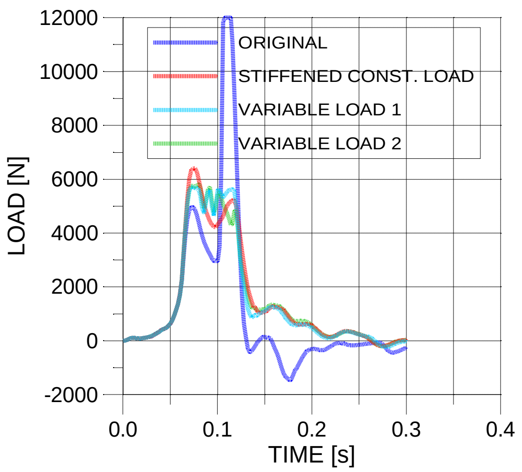


Fig. 21 – Dummy lumbar spine load

As shown in the plot of fig. 20, the new limit load for the energy absorber is increased from the value of 9430 N (8200 N + 15% dynamic hardening) to the value of 12300 N (10700 N + 15% dynamic hardening).
A second and more refined solution is instead found in a variable stiffness device, i.e. an energy absorber that after the elastic ramp does not reach a constant load level, but changes it as a function of the stroke. From the manufacturing point of view this is a more complex solution, but absolutely feasible with a deformable element that, for instance, has a non-constant cross section.
The optimisation of the energy absorber load profile is performed automatically by using a software recently included in the VEDYAC package, described later on: the user must define the target function that must be maximised or minimised (lumbar spine load), the function that must be parameterised (load profile of the energy absorber), the number of points that will define this function and the constraint (bottoming condition).
The optimiser has generated two variable load profiles, which actually do not differ significantly, as is clearly shown by the plots in fig. 20.
The use of variable load systems shows a 9% reduction in the spine force, which is clearly obtained by increasing the spine load uniformity around its maximum. Probably better results could be obtained by defining more points in the energy absorber profile, but this would imply more difficulties in the manufacturing of the device.

OPTIMISATION ALGORITHM

The energy absorber optimisation is performed by means of a genetic algorithm, a well-known technique [1].
The total number of evaluations, for the objective function, required by a genetic algorithm is often greater than the number of evaluations required by a gradient-based optimisation algorithm. However, genetic algorithms are hardly ever trapped by local minima, which allows finding a near global optimum of the objective functions. Furthermore, they are widely used when derivatives
of the objective function are not available, as in this case, and have already successfully been used for the optimisation of helicopter seats [2].

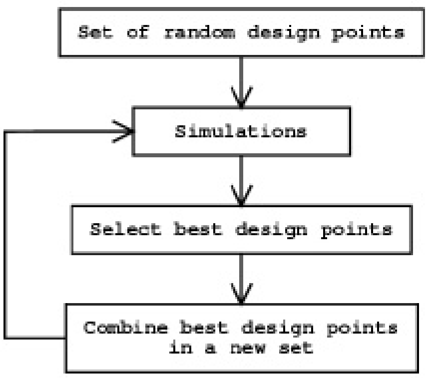
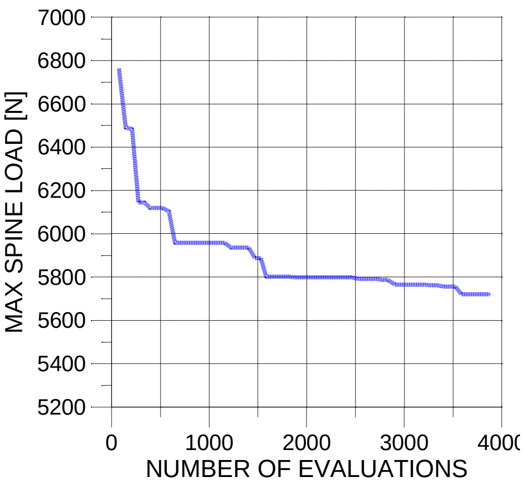


Fig. 22 – Flow diagram for the genetic algorithm

A simple genetic algorithm allows optimising unconstrained or bound-constrained problems. At first, the objective function is evaluated for a set of random design points. After this first set of evaluations, design points leading to better objective functions are preserved and mixed with each other to build a new set of tentative design points (fig. 22).
For the problem at hand, the unknown energy absorber load-stroke law is approximated with a continuous piecewise linear function. Ten variables, each ranging from 5 to 20 kN, are used to define the load-stroke law. The objective function is defined as the maximum lumbar load of each simulation.



A total of 75 different design points are randomly generated and fed to the optimisation algorithm; the selection and recombination of the best design points is then performed 62 times, for a total of about 4000 simulations.
Fig. 23 shows the best solution (i.e. the minimum lumbar load) as a function of the number of evaluations, or simulations. The best solution found with the initial, random set of design points leads to a maximum lumbar load of 6.76 kN. This value is slightly higher than the optimal solution obtained with

the constant force law. However, the maximum lumbar load quickly drops to 6.15 kN after about 270 simulations.
The convergence of the optimisation slows down as the optimal solution is approached.
Despite the high number of VEDYAC runs requested, a single 200 ms simulation requires only about 12 seconds on an AlphaStation 600A 5/500 with a 500Mhz 21164A CPU, for a total optimisation time of about 13 hours.

CONCLUSION

Seats have considerably increased helicopter crash survivability in the past 10 years. Even if the experimental approach to the problem remains the most direct evaluation tool and is requested by the aviation Standards, a numerical analysis can support the tailoring of the safety system, especially when its mechanical parameters become complex and testing is expensive.
In the case here reported, the seat energy absorber is no longer considered the classic constant load device, as already observed by other researchers in the last few years.
A variable load absorber is numerically optimised by genetic algorithm techniques, leading to a further reduction of the anthropomorphic spine load, with respect to a constant level absorber.
A question that remains open is: will it work with a human body? As a matter of fact a variable energy absorber able to reduce the lumbar load of an anthropomorphic test dummy may have a different response on a human body: non-linearities in the dynamics of an anthropomorphic test dummy, its interaction with the seat surfaces and the eigenmodes may play a relevant role in the spine reaction: a test dummy is certified on the basis of its response to high loading, with minor attention to its frequency modes, and a variable energy absorber could emphasize the differences in spine response between anthropomorphic dummy and human body.
Further investigation on the biofidelity of dummies in this area could now be necessary, to ensure that optimisation of energy absorbing systems is effectively oriented not only to dummy occupants.

HELISAFE PARTNERS

The Helisafe project started on February 2000 and ended on March 2003, within the 5^{TH} Framework Programme of the European Commission. The partners involved are as follows: Autoflug GmbH (D), CIRA – Centro Italiano Ricerce Aerospaziali (I), DLR – Deutsches Zentrum für Luft- und Raumfahrt e.V. (D), Eurocopter (F), Martin-Baker Aircraft Company Ltd (UK), Politecnico di Milano (I), Siemens Restraint Systems GmbH (D), TNO – Netherlands Organistion for Applied Research (NL).

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