MULTI-OBJECTIVE GENETIC OPTIMIZATION OF HELICOPTER SEATS UNDER CRASHWORTHINESS REQUIREMENTS

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Abstract

The focus of this work is the design and optimization of a typical helicopter seat under crashworthiness requirements. In particular, the energy absorption devices of the seats were optimized to reduce the lumbar spine load and to avoid bottoming phenomena.

The research approach consisted on the development and validation of a detailed finite element model of the seat and of an antropomorphic crash test dummy. The model was then used to simulate the test conditions required by FAR/JAR Standards. On a second stage, an optimization procedure of the energy absorption devices was carried out by means of genetic algorithms coupled with the response surface method.

The optimization procedure identifies a configuration of the energy absorbers that allows to minimize the lumbar spine load, proving to be an accurate and cost-effective tool in the design process of the helicopter seat.

1 Introduction

The safety of helicopters occupants in an accident event is achieved by the mutual contribution of the landing gear, the helicopter subfloor and the seat. The requirements on helicopter seats are particularly stringent because the seat itself provides an important contribution to the energy absorption features of the system. The FAR/JAR specifications require dynamic full-scale crash tests to verify the effectiveness of the seat. To meet the requirements, the typical crashworthy seat is often endowed with energy absorption devices. In fact, the typical helicopter seat consists of two separate parts: the sitting and the vertical tracks anchored to the cabin floor. The sitting is constrained to the vertical tracks by means of two sliding joints. The energy absorption devices prevent the movement between the sitting and the tracks. Different energy absorbers have been designed for this purpose. Two widely used techniques are based either on plastic deformation or on scraping of metal. The first category of devices was considered in this research. The energy absorption device consists of a metal tube with circular cross-section that, when activated, is permanently deformed, being drawn through a pair of wheels. The force level of the device is a function of the material properties, geometry and clearance between the wheels. This classical approach leads to an absorber that, after a short elastic deformation, has a constant load response. A variable load response, however, could be achieved by varying the cross-section along the absorber.

Absorbers are designed and tuned as to limit the lumbar spine load of the occupant, keeping it below the tolerable value of 6670 *N*. The effectiveness of the system is assessed by means of dynamic full-scale testing, measuring the lumbar spine load on an antropomorphic dummy.

The tuning of the energy absorbers may require several crash tests. Significant costs are involved, considering that in every test the seat may need to be replaced because it undergoes significant deformations.

Numerical analysis in the form of dynamic finite element analysis proves, therefore, to be an accurate approach in the design and tuning process of the seat and its absorbers. The dynamic, nonlinear, explicit finite element code LS-DYNA was used in this research [3].

To further reduce computational costs, finite element analysis may be coupled with numerical optimization procedures to identify the most promising configuration of the absorbers.

2 Seat Description and Finite Element Model

The seat is entirely made of a lightweight aluminum alloy. The main parts that compose the structure are the legs, the lateral reinforcements and the sitting for the passenger. Other reinforcement elements can also be identified underneath the sitting and behind the seat back, as well as in a rear cross that allows the load transfer mechanism between the legs. The sitting of the actual seat is also covered with a soft padding and endowed with a headrest for the comfort of the passenger.

The peculiarity of the helicopter seat considered in this reasearch lies in the fact that the sitting can slide with respect to the legs. This is made possibile by two rails in the inner part of the legs that lie in two guides obtained in the lateral reinforcements of the sitting. Two shock absorbers prevent this sliding motion until they are activated in case of an impact with a vertical component of velocity.

The connection between legs and sitting is realized such that it can tolerate small deformations or disalignments, in order to guaratee the functionality of the absorbers.

Finally, the legs present four notches at their ends that allow the connection of the seat to the cabin floor of the helicopter.

2.1 Seat Finite Element Model

A detailed finite element model of the seat was developed. The seat was modeled entirely using Belytschko-Tsay shells. Connections are realized with spotweld elements, rivets and by merging the nodes of different parts, in order to reproduce the actual connection scheme of the real seat. The model is shown in Figure 1.

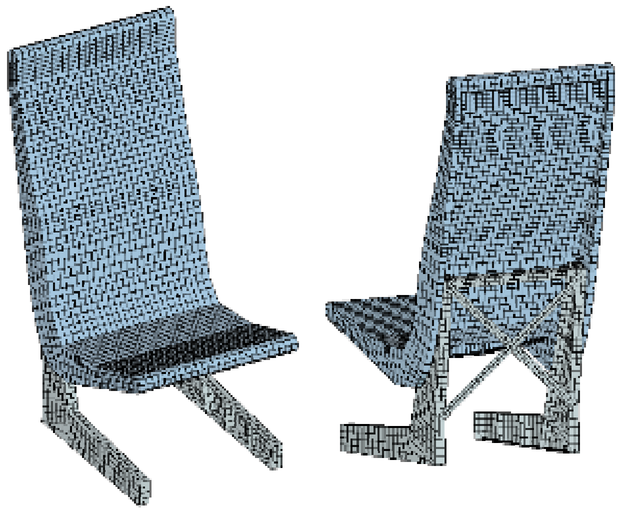

Fig. 1. Finite element model of the seat.

The two main parts of the seat, the sitting and the vertical tracks are connected together by means of two sliding joints. The energy absorbers are connected to the upper and lower parts of the seat preventing the sliding motion of the two parts. These devices were modeled using discrete elements, in order to evaluate different load-displacement curves.

The material was modeled using a piecewise linear material model. In particular, aluminum was modeled as a linear elastic-perfectly plastic material.

Contact surfaces were defined between the interacting parts of the seat. A surface-to-surface contact algorithm was used for the interaction between the rear cross and the vertical tracks. A nodes-to-surface contact algorithm was used instead to take into account the interaction between the seat tracks and the test sledge, as well as for the contact between the sitting and the tracks during the sliding motion in the event of a bottoming phenomenon.

The seat is rigidly constrained to the test sledge, explicitly modeled with shell elements as well. The deceleration history prescribed by the specifications is imposed to the sledge by means of a boundary condition option available in the code.

2.2 Anthropomorphic Dummy Finite Element Model

A finite element model of an aeronautical Hybrid III has been developed and validated for use in this reseach. The model reproduces faithfully the 50th-percentile crash test dummy used in helicopter seats testing, including 106 parts. Several parts are modeled with deformable materials, using a viscoelastic material formulation or a low density foam formulation for the rubber parts and a plastic kinematic material model for bone elements modeled as deformable (i.e., the ribs). Where deformations are not deemed significant, the elements are modeled as rigid. The parts are connected by revolute and spherical joints in order to reproduce the correct degrees of freedom of the dummy.

The dummy model includes specific elements, like accelerometers elements, to collect data in the same way as in the full-scale tests. A load cell is also located in the lumbar spine by measuring forces and moments in the spherical joints used to define the correct lumbar degrees of freedom.

The dummy was placed on the seat and constrained by explicitly modeling a four-point harness, connected to the seat model using spotweld elements. The harness was modeled using membrane elements and calibrating an elastic material model.

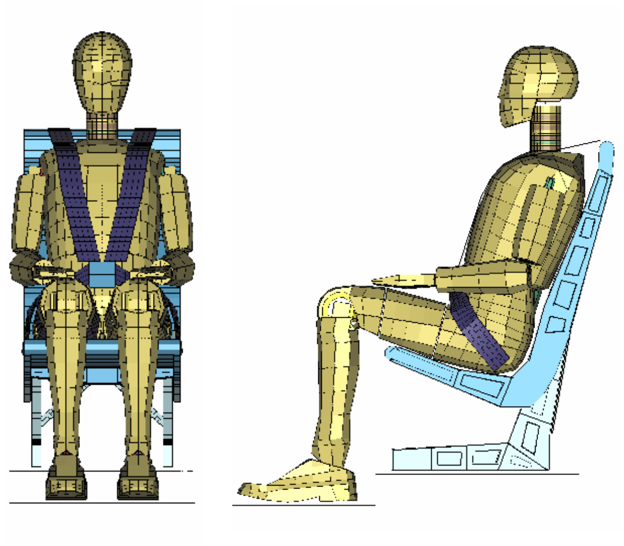

Fig. 2. Finite element model of seat and anthropomorphic dummy.

The complete model is shown in Figure 2. The mutual interaction between the seat and the dummy, as well as the interaction within the parts of the dummy itself, were taken into account by the definition of contact interfaces between the parts.

A surface-to-surface algorithm was used between the dummy and the sitting, as well as between the body of the dummy and the four-point harness.

2.3 Numerical Simulations and Results

The final model was validated by simulating the conditions of the "Down Test" prescribed by FAR/JAR specifications. The deceleration pulse prescribed for the test is shown in Figure 3.

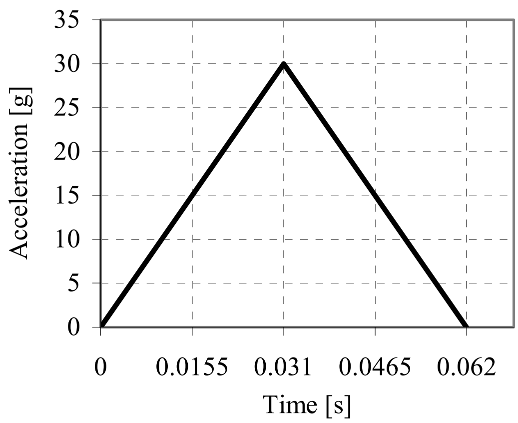

Fig. 3. Deceleration-time history for "Down Test" according to FAR/JAR specifications.

The configuration of the test requires the seat (i.e., the helicopter) to have a 60-degrees pitch angle with respect to the direction of the velocity, with the pitch axis lying in a vertical plane defined by the velocity vector and the longitudinal axis of the helicopter.

The model was then validated by means of preliminary experimental tests. A good numerical-experimental correlation was achieved in terms of acceleration values as well as in terms of the global response of the dummy.

The numerical and experimental correlation for the time-history of the lumbar spine load is shown in Figure 4.

The simulated event lasted 0.2 s., corresponding to a CPU time of approximately 9 hours and 10 minutes using a standard personal computer with an Intel Pentium 4, 1.7 GHz.

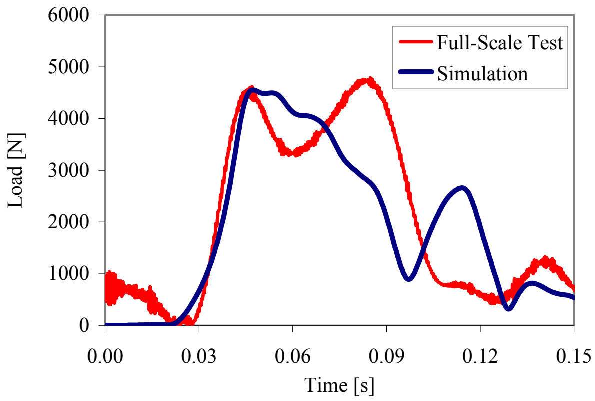

Fig. 4. Lumbar spine load time history, comparison between full-scale test and numerical simulation.

3 Energy Absorbers Optimization

The properties of the energy absorption device are related to its load-displacement curve. This relation can be tuned to minimize the lumbar spine load on the occupant. In particular, an elastic-plastic curve with kinematic softening or hardening was evaluated. The curve is defined by two values of force F1 and F2, as shown in Figure 5. By changing these force values within a reasonable domain, it is possible to obtain a broad range of configurations. If the force values are equal, a constant-load response is achieved. On the other hand, if the the first value of force is greater or less than the second value of force, a force-hardening device or force-softening device is considered, respectively. In particular, the elastic modulus was maintained for all the configurations, while the tangent modulus was varied.

The optimization procedure searches within the optimization domain for the configuration that minimizes the lumbar spine load, thus complying with the FAR/JAR requirements. Among the allowable configurations of the absorbers, solutions that provide larger residual energy absorption capabilities are preferred. These capabilities are measured on the basis of the residual available stroke of the devices.

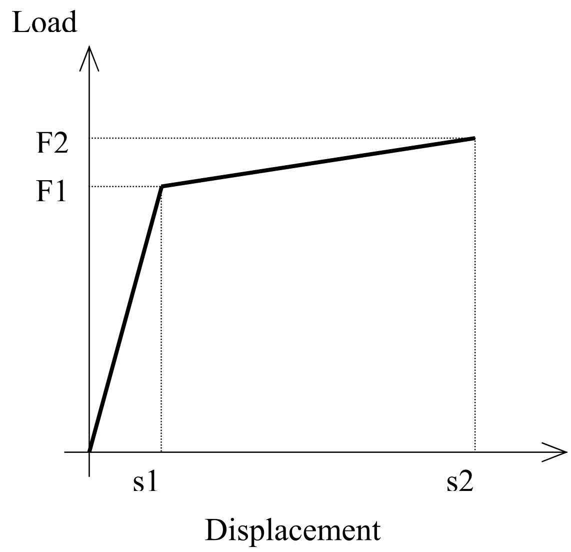

Fig. 5. Force-Displacement curve of the energy absorbers.

3.1 Genetic Algorithms

Genetic Algorithms (GA) are a well known approach to solve optimization problems. Their original formulation [5], as proposed by Holland, is suggested by the natural evolution: better individuals have more possibilities to hand down their characteristics in future generations. As originally formulated, GA can be used to perform single objective maximizations considering the objective function as fitness.

The search for the Pareto set is carried out by using a Multi-Objective Genetic Algorithm (MOGA) obtained by modifying the original formulation in order to simultaneously consider two or more objectives.

The algorithm used in this work is based on a binary DNA codification of 24 bits, 8 for each design variable. Only the three basic operators are used: selection, cross-over and mutation. Constraints are introduced using weighted exponential penalties functions while minimization problems are formulated using the opposite of the original objective function as fitness.

A ranking selection method, based on the definition of non-dominated points, is used to identify the Pareto set in case of multi-objective optimizations. Accordingly, during the optimization procedure a rank value is assigned to each individual of the current generation. The solutions with lower rank are non-dominated and, therefore, selected as Pareto-optimal set. Since the member rank is minimized throughout generations, the Pareto set is refreshed at each new algorithm iteration.

3.2. Response surfaces

Since Genetic Algorithm generally requires a number of function evaluations greater than the gradient-based optimization procedures, the computational efforts are further reduced by using Radial Basis Functions as global approximation method.

Radial Basis Functions are an interpolating scheme used to describe the behavior of non-linear functions once a set of initial sample points is known. The approximation is built through a linear combination of radial functions each one centered in one of the initial sample points, as described in details in [6, 7].

Particular attention has to be paid in the definition of the initial sample points since their positions directly affect the final accuracy of the approximation.

In this work, a regular grid of 5x5 equally spaced sample points is used to build the response surfaces in the two-dimensional domain of interest. Thus, a total number of 25 finite element analyses were performed changing the force values F1 and F2 of the seat absorption devices from 2000 *N* to 6000 *N*.

Two distinct response surfaces are then defined: the first one is used to approximate the maximum lumbar spine load while the second one is used to approximate the final stroke of the absorption devices. The obtained response surfaces are shown in Figures 6 and 7, respectively.

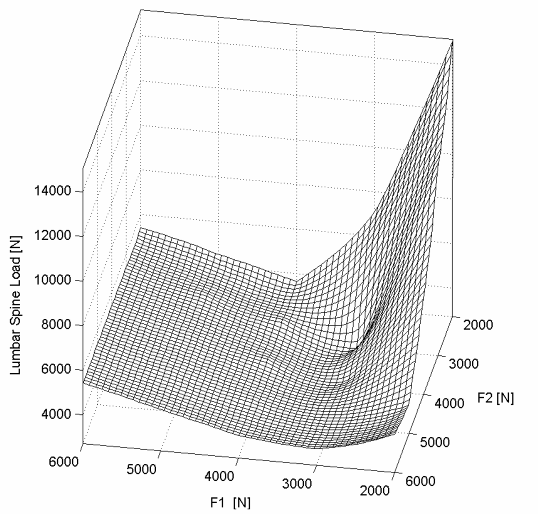

Fig. 6. Response Surface of the lumbar spine load.

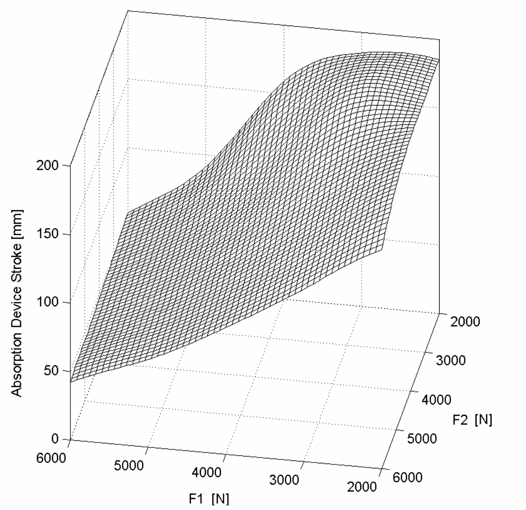

Fig. 7. Response surface of the absorption device stroke.

Increasing the force level of the devices (i.e., F1 and F2), the lumbar spine load on the occupant increases. However, it is not advatageous to arbitrarily reduce the load level, since below a certain value, bottoming phenomena may occur. This fact is apparent in Figure 6: when F1 is set below 3000 N and F2 decreases, the lumbar spine load increases dramatically. Figure 7 shows that in these conditions the full-stroke of the absorbers is reached.

3.3 Trade-Off Between Lumbar Spine Loads and Absorption Device Strokes

A preliminary multi-objective optimization is carried out by minimizing both the lumbar spine load and the absorption device stroke within the considered domain.

This problem formulation is motivated considering that, once the lumbar spine load has been defined, the best absorption device is the one that provides the minimum stroke. In fact, bottoming phenomena can be avoided, even in the case of a more severe accident.

A number of 20 individuals and 100 generations are used in the genetic search for the Pareto set, together with a crossover probability of the 0.55 and a mutation probability of 0.15. Figure 8 shows the identified Pareto curve, while Figure 9 shows the corresponding values of F1 and F2.

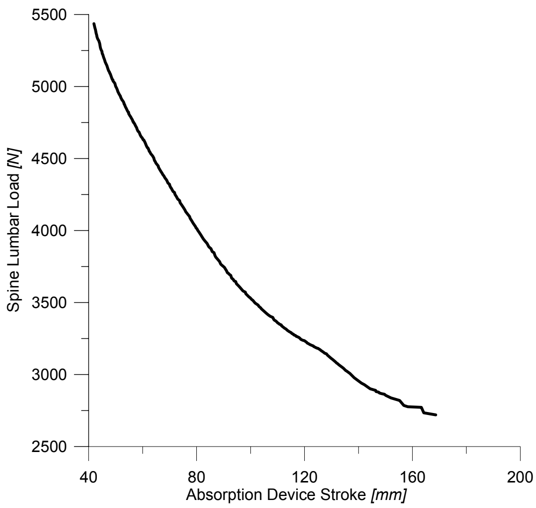

Fig. 8. Pareto set of the spine lumbar load vs. the absorption device stroke.

As more absorption capabilities are exploited, by allowing a higher stroke of the energy absorbing devices, lower values of lumbar load are observed. These conditions are achieved by reducing the load level of the devices. In particular, the first value of force (i.e., F1) strongly influences the lumbar load level, but only in a range of final stroke between 50 *mm* and 120 *mm*. In fact, above a maximum stroke of about 120 *mm*, as shown in Figure 9, it is necessary to reduce both levels of force F1 and F2. In this field the reduction of F2 follows a steeper curve than the one for F1.

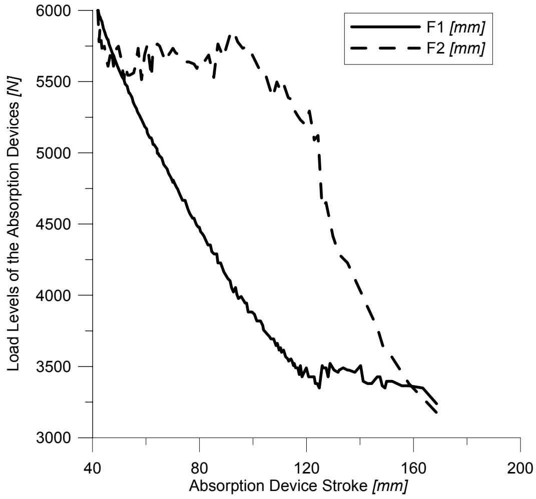

Fig. 9. Design variable values corresponding to the previous Pareto set

3.4 Lumbar Spine Load Minimization

The obtained results clearly show that an optimal trade-off might exist between the lumbar spine load and the absorption device stroke. However, as it happens in many practical problems, the identification of the Pareto set is only a part of the whole optimization process since a single final feasible solution is required. In these cases, decision criteria must be applied to identify the final solution.

For this purpose, three different absorption device configurations were investigated by minimizing the lumbar spine load and by setting the following limits to the devices stroke, respectively: 50, 100 and 170 *mm*. The results of these new genetic optimizations are shown in Table 1.

Stroke constraint	Optimal solution F1*[N]*	F2*[N]*	Load*[N]*	Stroke*[mm]*
< 50	5600	5515	5001	49.9
< 100	3850	5655	3530	100.0
< 170	3240	3145	2715	170

Tab. 1. Results of the single objective optimizations.

It is apparent that the points identified by these single objective optimizations are practically superimposed to the Pareto set previously identified. This fact proves the capabilities and the robustness of the adopted optimization procedure.

The first and the second final configurations were verified by means of further finite element analysis. Table 2 provides a comparison between the results of these finite element analyses and the results obtained by the response surfaces in the optimization process. As shown in Table 2, the maximum percentile errors of the approximation are within 10 percent.

Configuration		Resp. Surfaces		FEM model	
F1 *[N]*	F2 *[N]*	Load *[N]*	Stroke *[mm]*	Load *[N]*	Stroke *[mm]*
3850	5655	3530	100.0	3614	98.9
3240	3145	2715	170	3005	168.6

Tab. 2. Results of the single objective optimizations.

As the response surface of Figure 6 shows, the third configuration represents the global minimum for the lumbar spine load within the selected optimization domain.

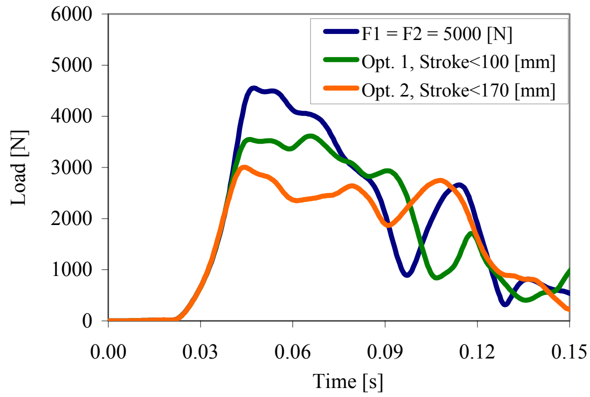

Fig. 9. Optimization results: lumbar spine load comparison between the optimized configurations and the initial one.

Optimization results are compared to the lumbar spine load time history of the initial configuration, in Figure 9.

Few sequential images of the finite element simulation with the absorber optimal configuration are presented in Figure 10.

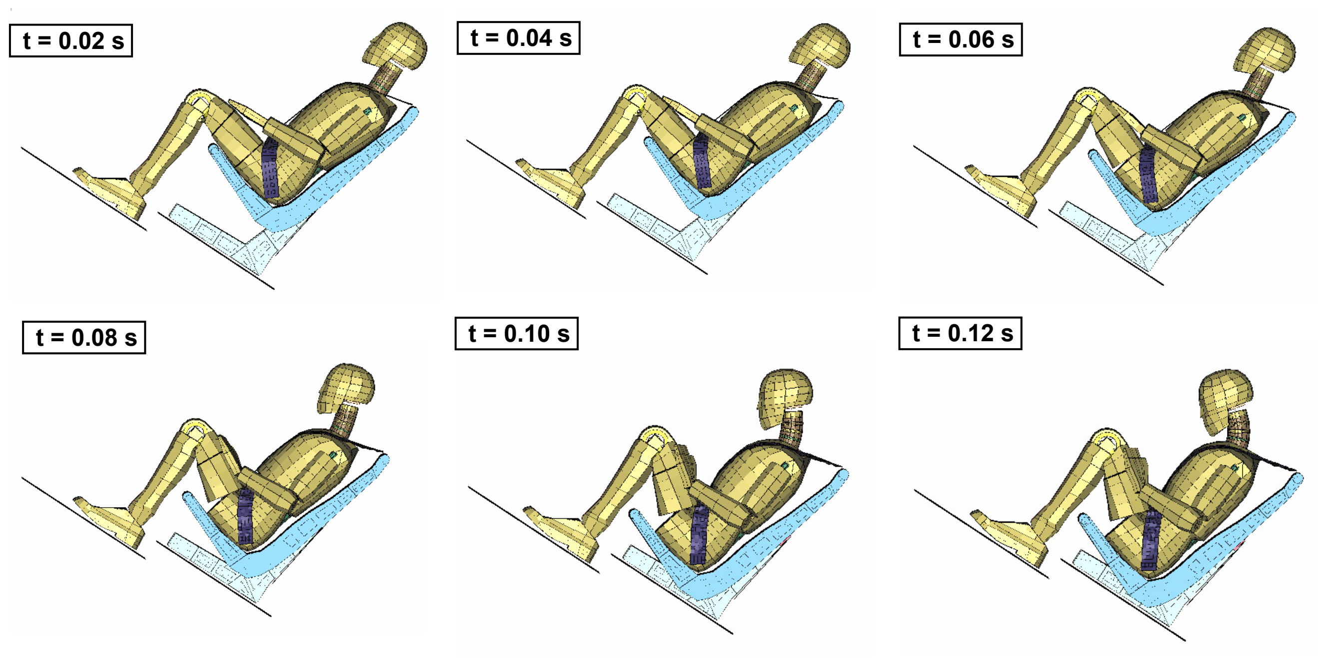

Fig. 10. Anthropomorphic dummy behavior for the optimized configuration of the absorbers with stroke of 170 *mm*.

4 Conclusive remarks

Helicopter seats strongly influence the safety of the passengers and the performance of energy absorbing seats can significantly contribute to the passengers survaivability in the case of crash landing.

In the case here reported, a numerical approach to the design of energy absorbing seats was considered. Even if the experimental approach to the problem remains the main evaluation tool and it is actually required by the Aviation Standards, the proposed approach can be of aid to design an effective system, thus minimizing the number of crash tests to be performed and, therefore, the costs of the design.

A finite element model of the whole seat and its passenger was developed and analyzed in the conditions prescribed by the standard specifications. Then, in particular, the attention was focused on the energy absorption devices. These devices were considered as variable load absorbers and a numerical optimization based on Genetic Algorithms coupled with Radial Basis Functions was carried out.

The results of the optimization procedure show that a trade off between the lumbar spine load on the occupant and the residual absorbing capabilities of the absorbers can be identified. In particular, the optimal configuration is characterized by an energy absorber that, after reaching a load level of approximately 3240 *N*, shows a slowly decreasing load-displacement relation. The lumbar spine load on the occupant reaches less than 50 percent of the tolerable value, while 15 percent of residual stroke is left to the absorbers.

The research is now in progress considering more design variables and different impact conditions. The formulation of the original optimization problem is enhanced accordingly. Indeed, the use of Multi-Objective Genetic Algorithm is now under investigation with the aim to simultaneously consider different impact angles and anthropomorphic dummies.

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