OPTIMISATION OF ENERGY ABSORBING SUBSYSTEMS FOR HELICOPTER VERTICAL CRASHES

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Abstract

The experience gained in the last decades on the development of crashworthiness helicopter structures indicates that occupants' protection can be achieved integrating different energy absorbing systems in landing gears, subfloor and seats. However, the mutual interactions between these different subsystems must be considered to achieve higher overall performances in case of crash events.

This work proposes a numerical approach for the evaluation of the overall undercarriage performance, basing on an hybrid multi-body and finite element approach. A hybrid scheme of the subfloor lay-out is integrated with a multi-body model of a crashworthy seat and an anthropomorphic dummy model. The modelling technique has been used to investigate and optimize the effects of local aspects on the overall crashworthy performances of the system such as the subfloor and the seat absorbing devices. Basing on the obtained results, the proposed methodology seems a promising approach to deal with the optimization of integrated structural systems, accounting for the mutual interactions of different subsystems, as well as multiple design and constructive constraints.

1 Introduction

The structural design of helicopters is nowadays increasingly influenced by the requirements relevant to the occupant safety in case of emergency landing conditions. The experience gained in the last decades underline that crashworthy performances is significantly enhanced with properly designed crashworthy structures [1,2].

The accelerations and the loads experienced by the occupants can be considerably reduced below the human tolerance limits by integrating energy absorbing systems in different locations of the helicopter structure: landing gears, subfloor and occupant seats. As a matter of fact emergency landings could occur with retracted landing gears, on water or on particularly soft soils. Accordingly, helicopters can not always rely only on the contribution of the landing gears to absorb the whole impact energy and then the subfloor and seat absorption characteristics become of major concern in generic crash conditions.

Occupant biodynamics during a crash is directly influenced by the interactions between the subfloor absorbing systems and the absorption characteristics of the seats themselves. These complex interactions could modify the survivability and the dynamics of the occupants in case of crash and must be adequately investigated.

All these considerations motivate the adoption of a numerical approach capable to analyse the whole system behaviour so to evaluate the global performances with minimum modelling efforts and computational costs.

The availability of such a method would also allow to investigate the effects of different energy absorbing components on the whole subfloor-seat layout even in the early design phases and for different crash conditions.

This work proposes a numerical technique for the evaluation of the overall subfloor performance, basing on an hybrid multi-body and finite element approach. After a rough description of common subfloor and seat design

criteria, the development and the evaluation of the modelling technique is presented and discussed with particular emphasis to a typical configuration of a light alloy subfloor equipped with a typical seat with an anthropomorphic dummy.
Thereafter, the proposed technique is used to deal with the optimal design of these integrated structural systems, namely subfloor and seats, accounting for their mutual interactions.

2 Subfloor and seat design criteria

The design of a crashworthy subfloor is actually achieved by introducing a series of absorbing components between the cabin floor and the lower fuselage skin. These absorbing elements are designed to collapse at controlled force levels during vertical impact [3,4]. The force levels at which the absorbing elements work can be estimated on the basis of the occupants' injury criteria and are functions of the available stroke, namely the vertical dimension of the subfloor.
Different types of components for crashworthy subfloors have been developed and presented in literature, focusing on the achievement of an axial collapse process at an approximately constant load, thus maximizing the energy absorbed at a given load level.
Light alloy as well as composite devices have been located in helicopter subfloors achieving high absorption capabilities [3-5]. These elements can be grouped in two main classes:

- diffused absorbers (such as shaped longitudinal webs and foam fillers) leading to a diffused energy absorption on a large area
- local absorbers (such as intersection elements, cross members) designed to absorb a large amount of energy in few areas such as the intersections between longitudinal and transversal beams.

Even if the optimal design of a single element suggests to maximize the absorbed energy per unit weight, this kind of approach would introduce high stiffness elements in the whole subfloor structure. In these cases, the strength and the stiffness of the overall subfloor structure, designed for normal flight and landing operations, might turn out to be inadequate to carry the crash loads provided by few absorber elements. Accordingly, loads must be properly redistributed among the absorbers to exploit their absorbing capabilities and to prevent localized failures that could occur with severe reductions of the absorbed energy.
As far as seats are concerned, they provide occupant protection by allowing a controlled stroke of the sitting during an impact with high vertical velocity. Therefore this kind of seat is composed by two parts: the first one is a fixed structure connected to the floor and includes the legs and vertical struts; the second one is a movable structure that includes the seat pan and backrest, as well as the safety belts attachments. The movable part can slide along vertical tracks integrated in the fixed struts.
Between the fixed and movable part a couple of energy absorbers is inserted. These absorber devices extend themselves under once a well defined load level is overcome, then unloading the occupant spine: the most common working principles are plastic deformation of metal parts and material scraping.

3 Hybrid modelling technique

Dynamic explicit Finite Element codes represent nowadays a well assessed and diffused methodology for the analysis of structural components in crash conditions. The crash performances of whole subfloors as well as of the single absorber elements realized in metallic and in composite materials have been analyzed with good experimental-numerical correlation in several works [8-9]. However, good experimental-numerical correlations require very accurate and detailed models as structures are subjected to changes of boundary conditions, resulting from contacts between different parts, failures of materials and/or structural joints. The modelling effort required to analyze complex absorption systems such as whole subfloor structures equipped with crashworthy seats and anthropomorphic dummies turns out to be prohibitive in preliminary design phases as well as to investigate different crash scenarios and/or to define optimization process and parametric models.

A different modelling approach can be developed describing the crash behaviour of absorption elements with a limited set of lumped parameters, for example their average force-stroke curves, and assuming that the local interaction between the elements could be described with enough accuracy using interface algorithms such as contacts, joint and kinematic constraints. These working hypotheses can be considered as valid as the objective of the analysis is a preliminary evaluation of the global system behaviour and, especially, in levelled crash conditions.

The application of the proposed hybrid modelling technique will be in the following discussed adopting the HKS/Abaqus explicit solver and considering an helicopter assembly of a typical subfloor, a typical crashworthy seat and an anthropomorphic dummy. The assembly parts will be briefly discussed in the next paragraphs.

3.1 Subfloor model

The subfloor system was modelled following a technique similar to the one already used and validated in a previous work [9]. The basic idea moved from the evidence that the behaviour of an energy absorption device presents common features even if different absorber typologies exist: an initial peak followed by a stable collapse phase at an approximately constant load and a final bottoming.

Load vs. shortening curve characterizing the absorber performances can be eventually obtained in separate tests or analyses and subsequently introduced in a model of the whole subfloor by means of a generalized non-linear and inelastic beam. The flexural and torsional response of such elements can be eventually used to roughly represent the stiffness of the intersections and of the webs under loads acting on the floor plane, while the axial response, uncoupled with the other degree of freedom, can be calibrated according to the axial load vs. shortening curve characterizing the energy absorbing behaviour as shown in Fig. 1.

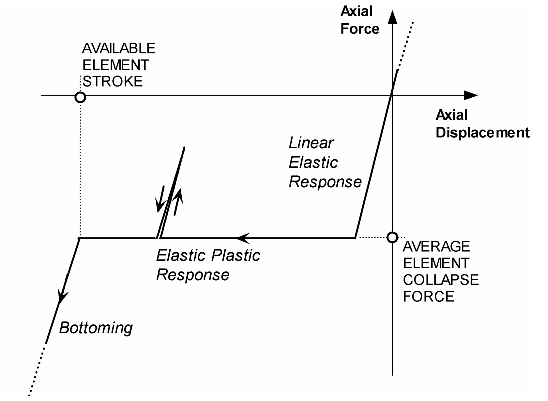

Fig. 1. Modelling technique for the energy absorbing system integrated in a subfloor.

Accordingly, the absorbing devices of the subfloor were grouped in a set of lumped stiffness elements and subsequently assembled to the cabin floor and the outer fuselage skin, modelled with shell elements. Longitudinal and transversal beams of the subfloor frame were modelled using beam elements with elasto-plastic constitutive law so to account for their true bending and axial behaviour as shown in Fig. 2.

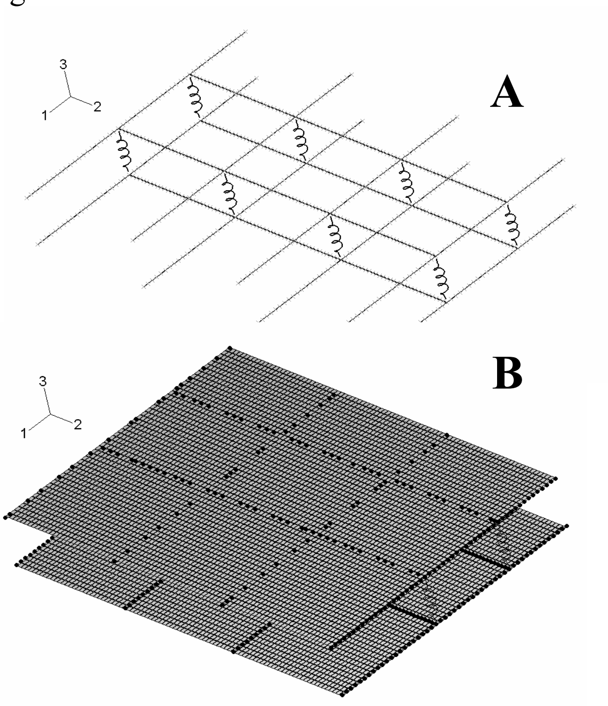

Fig. 2. Subfloor model with lumped absorbing devices and detailed FE subparts.

The connections between the different parts of this hybrid scheme were modelled by means of diffused bilateral constraints. A contact was set between the floor and the skin surfaces to take into account the final bottoming of the subfloor. Upon the cabin floor three helicopter seats were be located to form the final system assembly. Finally, an Hybrid III dummy was seated on the central seat of the assembly.

3.2 Seat model

The seat model is a very simplified system made of two rigid bodies (fig. 3): one represents the fixed seat part connected to the beam frame of the floor by 4 attachments; the other rigid body represents the seat movable equipment (seat pan, backrest and belts attachments). The two bodies were connected by 3 translational joints allowing a relative vertical translation of the parts; the energy absorbers characteristics were concentrated in the central translational joint and were defined by a beam in parallel with a slack spring: the beam provides the elastic-plastic response and the spring provides the bottoming response, after ending its slack that is tuned to the allowable stroke.
The seat surface was modelled with a finite element scheme to better exploit Abaqus contact algorithms.

3.3 Anthropomorphic model

The occupant model represents a 50th percentile Hybrid III anthropomorphic test device, in the FAA version to be used for aviation seat dynamic tests. The Abaqus model was derived from a LS-Dyna full finite element model, already validated in all its sub-parts and used in previous works [10]. The initial model is here converted into a hybrid finite element and multi-body model.
The lumbar spine (Fig. 4) in the test dummy is a complex component, made of steel discs and rubber blocks with an internal steel cable: a finite element representation was then chosen for this component. Moreover the lumbar load is the principal injury criterion applied in the acceleration conditions considered in this work and then the compressive response of the lumbar segment is of great importance for the load measurement.
Head, pelvis and limbs have geometrical and mechanical properties that better fit in a multi-body scheme.

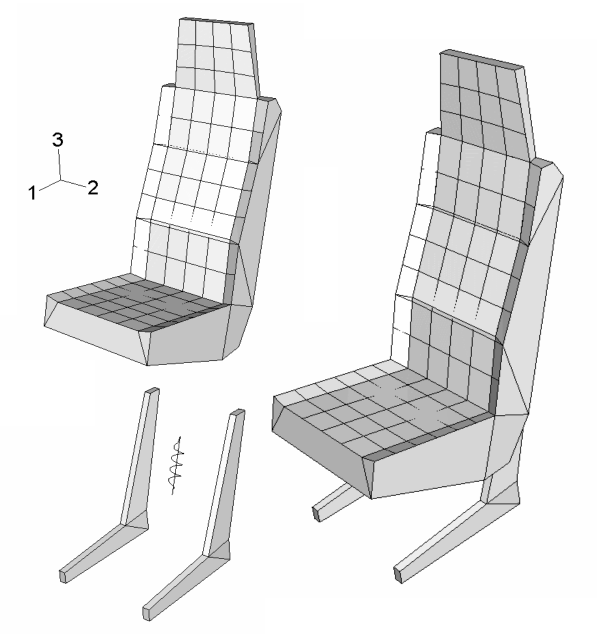

Fig. 3. Seat Model.

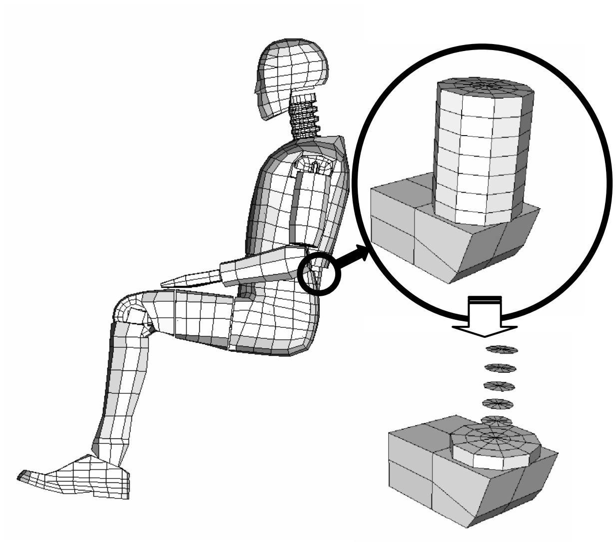
Fig. 4. Dummy Model.

Thorax and neck were eventually condensed into rigid bodies, because the load conditions considered in this work do not need an accurate reproduction of the thorax compressive characteristics and neck flexion and extension.

The final model is then made of an assembly of different body segments, partly consisting of finite element modules but mainly of rigid bodies, connected by generalized joints that represent the articulations and capable of mutual contact interactions. A modular definition of the different body segments allowed to simplify the positioning of the dummy on different seats, that is operated by an external code that modifies the reference systems of each module with no violation of the constraints (articulations).
The hybrid scheme here described allows a biofidelic representation of the anthropomorphic test device and, in the same time, reasonable computational times.

3.4 Validation of the anthropomorphic and seat model responses in impact tests

The reliability of the numerical analyses carried out using the developed models of the anthropomorphic test device and of the seat was assessed taking into consideration the experimental results of two impact tests.

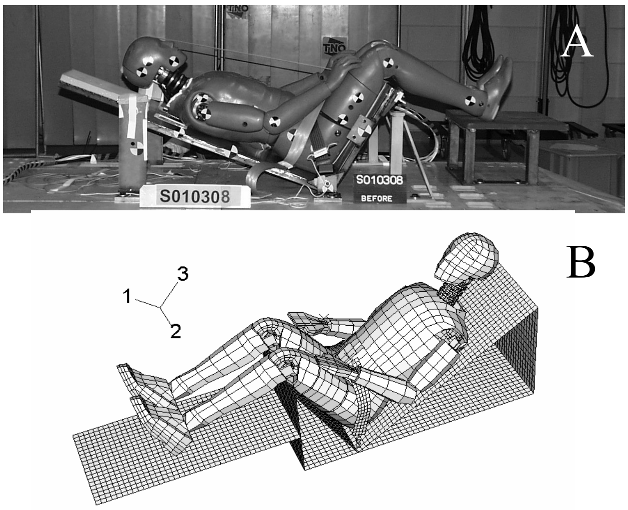

Fig. 5. Experimental set-up and model of a test with a rigid seat.

Both tests are referred to impacts characterised by triangular acceleration pulses in a direction inclined at 60° degrees around the helicopter pitch axis. This test set-up, that is requested by the FAR and EASA regulations for seat certification, is shown in Fig 5. The first test was performed with a 50th percentile Hybrid III dummy using a very stiff steel seat, so that the test response was uniquely determined by the behaviour of the anthropomorphic test device [11]. The test was analysed adopting the previously described dummy model and a finite element scheme of the rigid seat made of shell elements, as shown in Fig. 5-B. Figure 6 shows three instants of the performed analysis, while Fig. 7 presents the numerical-experimental correlation of the lumbar spine load obtained filtering the numerical results with 60 Hz and 180 Hz cut-off frequency, respectively.

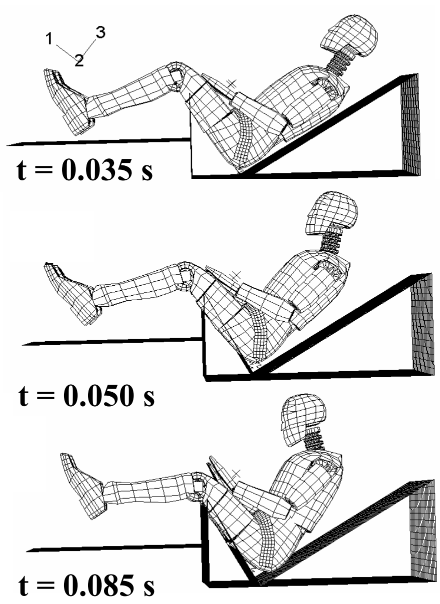

Fig. 6. Numerical analyses of a test with a rigid seat.

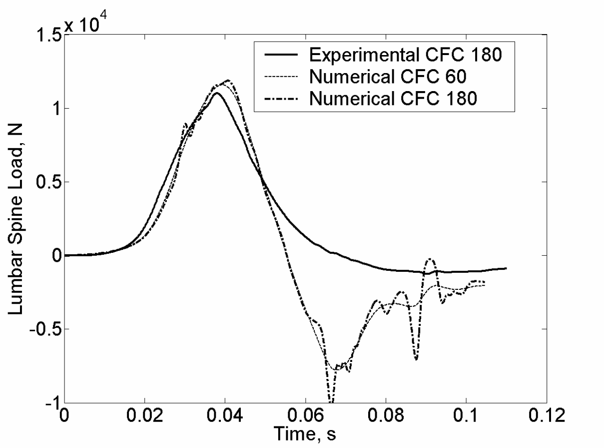

Fig 7. Numerical-experimental correlation of the lumbar spine load in the rigid seat test.

The second test was performed with identical set-up, using a deformable seat endowed with an absorber located between the moveable and the fixed part of the seat. The absorber was designed to be activated at an axial load of 9500 N and to maintain a constant load level during its stroke. In the experimental set-up, the stroke was limited to 115 mm. Figure 8 shows three instants of the analysis of the test. The central translational joint between the two parts of the seat model was characterised with an elastic-perfectly plastic response with yield at 9500 N, while the slack spring modelling the bottoming was calibrated to allow a stroke of 115 mm.
Figure 9 presents the numerical-experimental correlation of the lumbar spine load and of the absorber stroke .

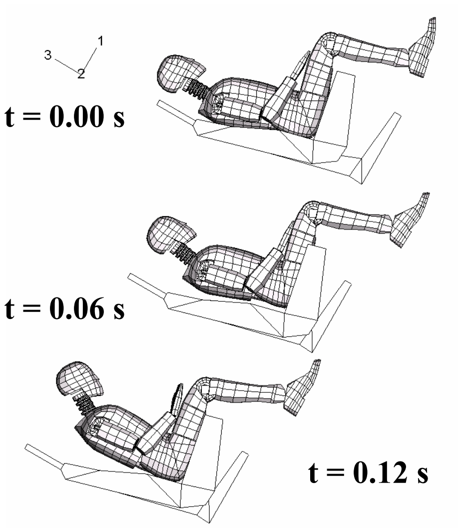

Fig. 8. Numerical analyses of a test with a deformable seat.

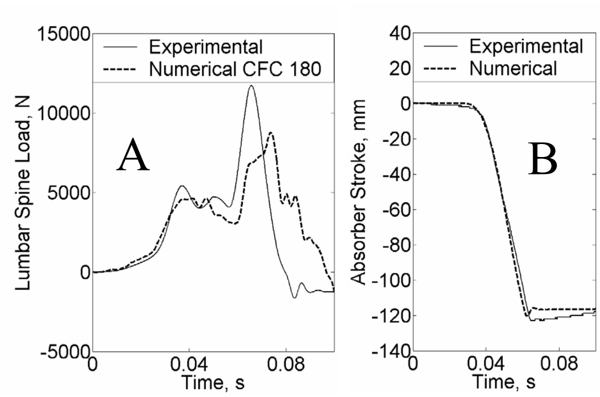

Fig 9. Numerical-experimental correlation of the lumbar spine load (A) and of the absorber stroke (B) in the test with a rigid seat.

Globally, the correlation between the numerical and experimental results obtained in the two analyses indicates that the adopted modelling technique is adequate to represent the basic aspects of the response of an anthropomorphic test device in impacts having a significant vertical component of acceleration.

3.5 Final assembly and parameterization

Subfloor frame, crashworthy seats and anthropomorphic dummy were finally assembled to constitute a single system. A model of the soil surface was finally introduced. A perfectly rigid surface was considered and modelled with rigid shells and a contact interaction between the fuselage and the soil.
The whole system assembly is shown in Fig. 10. For each seat, the legs were constrained to the floor beams in four points, as in the real installation.

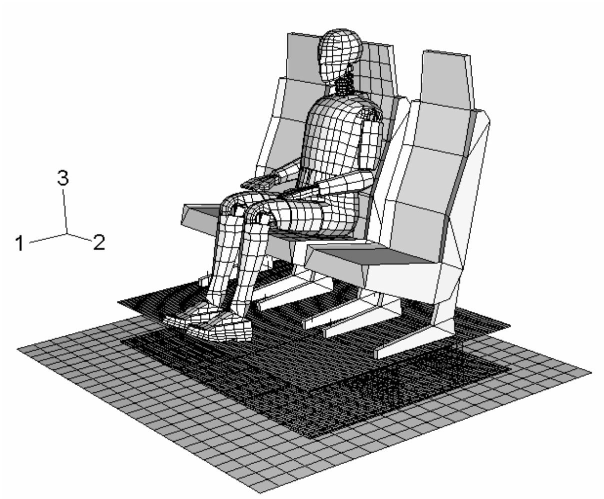

Fig. 10. System assembly (subfloor, seats, dummy).

Since the main objective of the work is the preliminary set-up of an optimization procedure able to account for the mutual interactions of the different parts, the numerical model was parameterized allowing to change the positions of the absorbers elements in the subfloor frame, the cross-section of the longitudinal and transversal beams as well as the seat absorbers. An intermediate interface has been built up to down-select the parameters to be used as design variables during the optimizations among the all used to define the model. In this way the

optimization loop can be easily defined without interfere with the model definition.
Moreover, the development of a parameterized model allows studying the behaviour of the system in different configurations. The number of occupants, and the mass to be decelerated in the impact, the distribution of the subfloor absorbers as well as the initial velocity conditions can be set modifying the parameter of the model.

4 Formulation of the optimization problem

From a general standpoint a crashworthiness optimization would aim at maximizing the energy absorption capability of the considered system and to limit the acceleration experienced by the occupants below the survivability limits.
This kind of problems can be formulated and solved in different ways depending on the design objectives, the constructive contraints and the requirements imposed by civil and military regulations. A classical approach dealing only with subfloor system is to minimize the total mass of the system guarantying a minimum amount of absorbed energy and limiting the system accelerations below prescribed limits as proposed in Ref. 9.
Similarly, the optimization of crashworthy helicopter seat could be oriented at the minimization of the lumbar load experienced by the occupants in predefined impact conditions as presented in Ref. 10.
The performance of the whole energy absorbing system is however significantly influenced by the available stroke. As the stroke often represents a constructive constraint and the maximum loads are prescribed by human tolerance limits, the theoretical maximum amount of impact energy that can be absorbed by the system is given. Hence, the system should be designed to exploit as more efficiently as possible the available stroke. These considerations and the availability of a model representing a whole energy absorbing system lead to a formulation of the optimisation problem focused on the minimisation of the overall stroke in a given impact condition meeting the lumbar spine load limit. Accordingly, the system would be designed to guarantee the maximum absorption capability in case of crash events more severe than those prescribed by regulations.

4.1. Optimization variables and domain

Even if the parametric model of the whole system previously defined would be able to modify the subfloor configuration relocating the absorption elements, redefining the longitudinal and transversal beam and defining different seat absorber curves, few design variables have been selected in this preliminary study.
A first working hypothesis was to fix the number, typology and position of the absorbing elements in the subfloor. The absorption capabilities were thus concentrated in 8 elements located at the intersections between longitudinal and transversal beams.
Exploiting the symmetry of the system, all the 8 absorbing elements are assumed to have the same behaviour, namely the same mean force level, handled as design variable X_1 in the system optimization. The domain of interest reported in Tab. 1 has been selected basing on the experiences gained in previous works and assuming a range of mean force for which it would be possible to manufacture real intersection elements.

		min	max
Intersection elements -mean force (kN)	X_1	5.0	30.0
Seat absorbers - initial force (kN)	X_2	2.5	12.5
Seat absorbers - final force (kN)	X_3	2.5	12.5

Tab. 1. Design variables and domain of interest.

Two other variables were used to describe the force-stroke curve of the absorbers located in the occupants' seats: the force level at which the absorber starts to work (X_2) and the final force level defining a bilinear absorber behaviour (X_3).

4.2. Objective and constraints

As above described, the system would be optimized minimizing the overall stroke. The

impact conditions were set to represent a vertical crash at 10 m/s, with all the three seats carrying the weight of 50th percentile dummies. Attention was focused on the performance of the central seat, where the dummy model was actually positioned. The effects of the occupants on the two other seats were introduced increasing the mass of their moveable parts.
The objective function has been defined as a weighted sum of the seat absorber stroke and the shortening experienced by the intersection element of the subfloor frame. The main constraint introduced in the problem formulation was the lumbar spine load required to be lower than a given level.
Another issue accounted for was the occurrence of bottoming of the absorber devices. In fact, bottoming phenomena should be generally avoided because they introduce strong concentrated load peaks very difficult to be numerically predicted. It was then decided to add two further constraints to prevent the bottoming of both the subfloor absorbers and the seat shock absorbers. Accordingly, the maximum stroke of the absorption element was constrained to be lower than the 0.95% of their maximum stroke. In this way the optimization algorithm can directly control and possibly avoid bottoming.
The formulation chosen for the optimization moves from simplified working hypothesis neglecting many constraints to be eventually accounted for in real-world applications such as maximum strain and local acceleration levels. Nevertheless, the proposed formulation seems particularly adequate to investigate the interactions between the different parts of the system defining a simple and global objective as well as a single generalized constraint directly related to the occupant survivability and capable to constraint indirectly the dynamics (acceleration and motion) of the whole assembly.
Concluding, the optimization problem was formulated as:

$$minimise \;\; \mathbf{max(}\, w_1 S_{Seat} + w_2 \cdot S_{Subfloor} \,\mathbf{))} \quad (1)$$

subjected to:

$$\begin{cases} \max(F_{Lumbar}) \le \overline{F}_{Lumbar} \\ \max(S_{Seat}) \le 0.95 \cdot S_{Seat}^{Max} \\ \max(S_{Subfloor}) \le 0.95 \cdot S_{Subfloor}^{Max} \end{cases} \quad (2)$$

where S_{Seat} and $S_{Subfloor}$ are the seat and subfloor strokes respectively, F_{Lumbar} and $\overline{F}_{Lumbar}$ are the actual maximum lumbar loads carried by the dummy model on the central seat and the corresponding maximum allowable value, fixed at 6000 N. Finally, $S_{Subfloor}^{Max}$ and S_{Seat}^{Max} are the maximum stroke of the absorption elements located on the subfloor and on the seats.
Limiting to this preliminary investigation and without loss of generality, a SQP algorithm was used to solve the optimization problem. In fact, the problem presents continuous design variables as well as objective and constraints. Hence, the relatively limited number of design variables and the limited amount of function evaluations required to build the Hessian of the problem iteration by iteration would allow the algorithm to exploit the benefits of a full line-search algorithm providing probably a faster convergence than the one obtained using other optimization algorithms.

4.3. Optimisation results

As shown in Fig. 11, the optimisation algorithm acted redistributing the absorbing capabilities from the subfloor to the seat absorbers. In fact the mean force of the subfloor intersection elements is progressively reduced up to 90% of the initial value while the force levels of the seat absorber are increased of a factor 2.

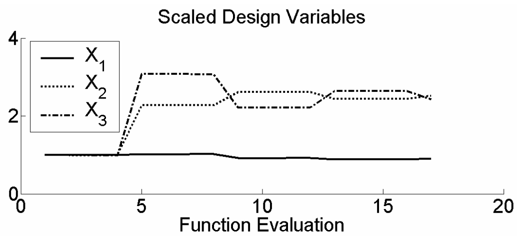

Fig.11. History of design variables in the optimisation process.

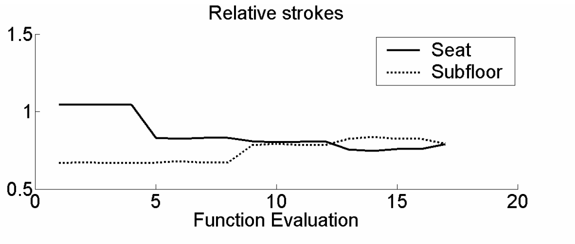

Fig.12. History of the relative strokes of energy absorbers during the optimisation process.

This behaviour is confirmed in Fig. 12 where the relative strokes are reported. In this respect, the maximum stroke of the subfloor results to be increased of about 15% percent better exploiting its absorption capabilities while the one of the seat absorbers has been reduced of about 25% mitigating the risk of bottoming shown in the first iterations. The final solutions exibits a meaningful reduction of the lumbar load that is contained below the 5000N starting from an unfeasible solution of about 6500N as shown in Fig. 13.

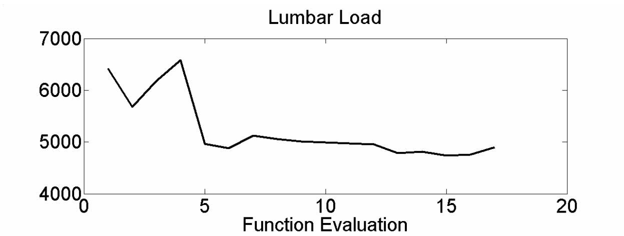

Fig.13. Variation of the lumbar spine load during the optimisation process.

The obtained results and the behaviour of the model can be further investigated comparing the initial solution with one of the optimised solution, chosen among the ones satisfying all the imposed constraint. Figure 14 shows a sequence taken from the optimised solution, while Figs. 15 and 16 presents the numerical time histories of the absorber strokes obtained with the initial and the optimised solution, respectively.

In the initial solution, as shown in Fig. 15, the seat absorber reaches the bottoming at about t=0.035 s, on the opposite the subfloor absorbers are activated later on and shortened at a very limited level. When the seat absorber reaches the bottoming, a further stroke of the subfloor is obtained. Limiting to the initial solution, Figure 17 shows how the lumbar load remain below the 3000 N before the seat absorber bottoming. Thereafter, it increases up to 7000 N, exceeding the imposed limits.

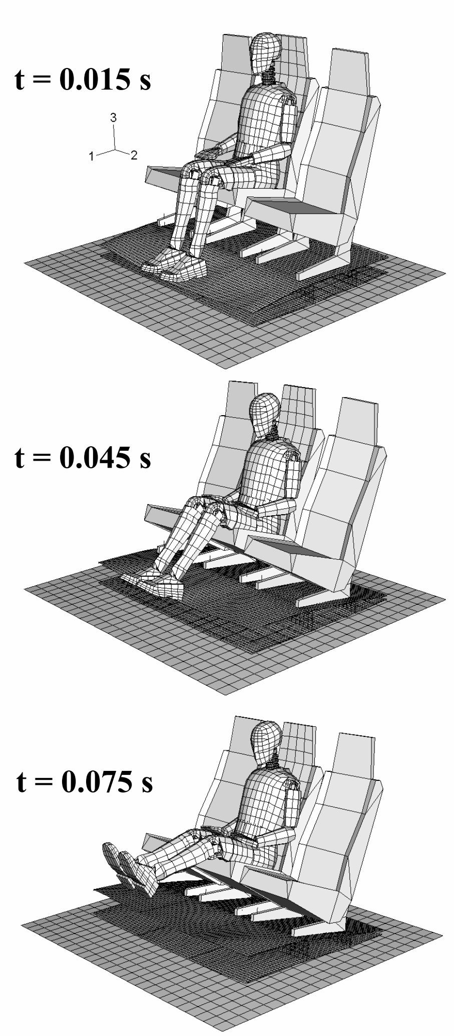

Fig. 14. Analysis of the vertical impact with an optimised solution.

4.3. Optimisation results

As it is shown in Fig. 16, none of the absorbers experience bottoming phenomena in the optimised solution. In fact, the subfloor absorbers are activated in a first phase of the impact, before t=0.02 s, limiting the lumbar spine load below the 5000 N level. At t=0.02 the seat absorber is activated and the whole impact energy is dissipated without exceeding the imposed constraint of 6000 N on the lumbar spine load.

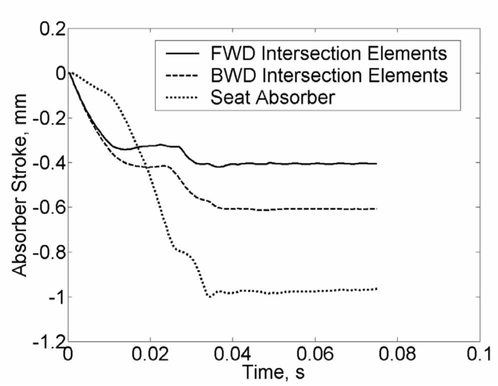

Fig. 15. Relative strokes of the energy absorbers in the initial solution of the optimisation process.

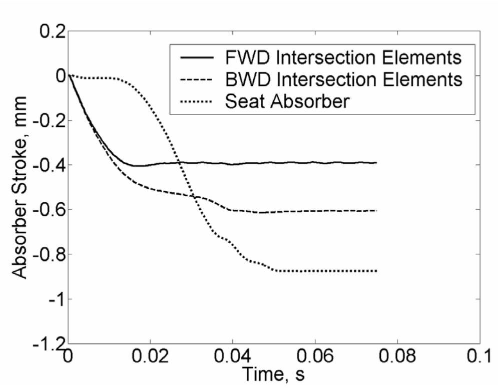

Fig. 16. Relative strokes of the energy absorbers in an optimised solution.

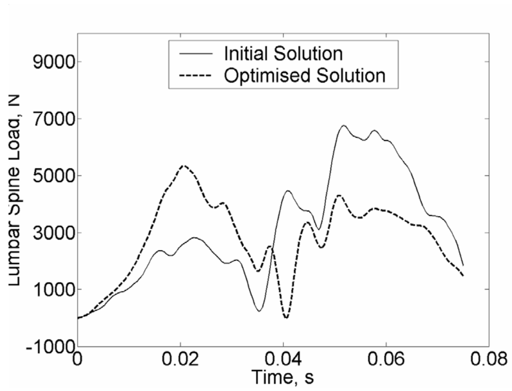

Fig. 17. Lumbar spine load in the initial and in the optimised solution.

5 Conclusions

This work proposed a modelling technique capable to model the whole energy absorbing system integrated in an helicopter structural lay-out to investigate and eventually to improve the structural crashworthiness in vertical impacts. Subfloor, seats as well as anthropomorphic test device were included in a numerical model developed combining the hybrid and finite element modelling capabilities of the HKS/Abaqus Explicit code. The developed seat and dummy models were assessed by impact tests obtaining an acceptable numerical-experimental correlation.

The limited computational efforts of the proposed approach compared to those of detailed finite element analyse allowed the setup of an optimisation procedure. The results indicate that the modelling technique and the adopted formulation of the optimization problem lead to identify interesting design solutions capable to dissipate the impact energy of a vertical impact at 10 m/s mitigating the risk of bottoming phenomena and maximising the absorption capabilities of the system in case of more severe crash events.

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