Paper 208

# A HYBRID MODELLING TECHNIQUE FOR THE ENERGY ABSORPTION CAPABILITIES OF A CRASHWORTHY HELICOPTER STRUCTURE

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## ABSTRACT

The design of modern helicopters is highly influenced by crashworthiness requirements aiming at increasing the survivability of the occupants in case of an accident. In the event of a crash impact, the helicopter structure must preserve a minimum survivable space and limit the forces and accelerations transmitted to the occupants and the payload. In order to limit the overall weight of the structure, this requirement has to be taken into account ever since the beginning of the design, introducing in the helicopter structure energy absorbing systems, mainly in the landing gear, the cabin subfloor and in the seats. Numerical analyses represent a valuable tool to support and guide the design process. Finite element techniques as well as multibody models can be used to address this issue. Both these approaches present advantages and drawbacks. A hybrid modelling technique has been validated conjugating multibody and finite element schemes: the multibody technique allows to obtain the overall behaviour of the structure while modelling relevant parts adopting a finite element method permits to gather more detailed information. This is the case of the lumbar spine of the anthropomorphic test device (ATD) used to evaluate the severity of an impact condition. The hybrid model of an ATD has been derived from an existing finite element model and it has been validated in different reference cases comparing the results obtained by the numerical analyses to the experimental evidences of the tests. The hybrid model of the ATD and of a crashworthy seat have been adopted to investigate the consequences of the introduction of a typical subfloor structure. A pure vertical impact has been considered and an experimental test has been performed. The subfloor structure has been modelled adopting a hybrid multibody/finite element approach and the typical force vs. stroke curve of the intersection elements of the subfloor has been derived from experimental tests. The lumbar load time history, obtained via numerical analyses, has been compared to the experimental curve. The hybrid modelling technique presented proved to be capable of obtaining the desired information in terms of deformation of the structure and of effects of the impact with respect to the biodynamics of the occupant. The most appealing features of this technique are represented by the reduced computational costs required to perform the analyses, the possibility to be adopted from the early stages of the design and to provide guidelines to design effective energy absorbing devices of the subfloor and of the crashworthy seat.

## INTRODUCTION

Crashworthiness requirements have a great influence in the design of modern helicopters and represent a challenging issue in order to improve the safety in the event of a crash and to increase survivability of the occupants in case of an accident.

In the event of a crash impact, the helicopter structure must preserve a minimum survivable space and the forces and accelerations transmitted to the occupants and to the valuable objects should be limited within tolerable prescribed levels.

The structure of the helicopter should be designed in order to be capable to absorb kinetic energy in many different possible impact scenarios, on a rigid surface as well as soft soils. Enough space has to be granted after the crash and the possibility to escape after the crash has to be provided. The velocity of impact of the occupant(s) against the surrounding cabin environment has to be limited to prevent more serious injuries and the structure has to be designed in order to prevent post-crash fire and the fuel spillage in dynamically survivable crashes.

Crashworthiness is not the only requirement that a helicopter structure has to fulfill: fatigue, flow tolerance and fail safety has to be considered as well. The final result should represent the best compromise between all these needs.

The landing gears, the subfloor and the seats are the structural parts most demanded to withstand crash loads [1, 2].

Crashworthiness studies date back in the 1950s in the automotive field and have been extended to the aeronautical field in the 1960s. Aim of these studies is to figure out the most common accident scenarios and to identify the impact parameters such as velocities, impact angles, kind of soils and to point out the existing relationships between the impact conditions and the crash forces, the structural failures and the injuries. These studies allowed for the definition of the static and dynamic load conditions to certify the airframe and its single components, such as seats, restraint systems and fuel tanks. SAE regulation [3] specifies crash conditions for the certification of civil rotorcraft seating systems, representative of vertical and horizontal impacts, considering a prescribed triangular deceleration pulse to be applied to the seat and fixing a limit, considered tolerable, for the lumbar load.

Ever since the 1980s, regulations require or recommend design criteria for crashworthy design [4]. The major concern is to determine the most representative impact conditions to be used ever since the early stages of design in order to prove the effectiveness of the safety systems proposed.

## CRASHWORTHY DESIGN

To limit the weight of the overall helicopter structure, crashworthiness issues have to be considered ever since the beginning of the design, providing for structural parts capable to carry the operational loads and to effectively absorb energy in the event of a crash impact.

The landing gears, the cabin subfloor and the seats of helicopters are often provided with energy absorbing systems designed to absorb energy collapsing in a controlled manner at a prescribed force level. The resulting increase in weight of the helicopter structure should be minimized and the normal operation capabilities should not be altered.

Experimental testing of aircraft structures, especially in crash conditions, is very expensive and complex due to the difficulties in reproducing the desired impact conditions. For this reason, experimental tests are performed only if strictly required and very late during the design process [5-9].

Numerical analyses can represent a valuable tool to support and guide the design process.

Experimental testing and numerical analyses can help to have a better understanding of the energy absorbing mechanisms activated in the event of a crash and to evaluate the time histories of displacements, velocities and accelerations in order to properly size the different components.

In vertical impacts, the landing gear is mainly responsible for the deceleration of the helicopter. In the following phases of the impact the effect of the subfloor crushing and of the seat energy absorber activation become more and more relevant.

Different techniques can be used to perform numerical evaluations [10-14].

The most effective techniques used to evaluate the performances of the structure are finite element and multibody models.

Finite element analyses are usually adopted for the detailed design and certification of single structural parts. These models allow for considering fast dynamics, geometrical nonlinearities related to large changes in the shape and very large displacements, material nonlinearities due to elastic-plastic behaviour and nonlinearities related to the contact interactions. Commercial codes implement many different material models capable to represent the typical behaviour of metals as well as composite materials. This modelling technique is very suitable to design single components but, besides the very high computational costs of large detailed models, it is not appropriate to consider mutual interactions between the different energy absorbing devices.

On the contrary, multibody models are capable to effectively address this issue, modelling functional as well as structural responses at subcomponent level, using elements with lumped properties. The behaviour of such subcomponents can be derived from detailed finite element analyses or experimental tests.

Multibody analyses performed considering the complete structure of an helicopter allow for studying the consequences of crashes in different impact conditions and require very limited computational efforts.

The biodynamics of the occupants and the interaction with the surrounding structure can be studied including in the model anthropomorphic dummies. Different possible configurations can be considered by means of this modelling technique at a reduced modelling effort.

Multibody models can be parameterized in order to determine the requirements for the energy absorbing systems and can guide the positioning and the distribution of the energy absorbing devices. Numerical analyses performed using this technique permit to identify the path followed by the loads due to the impact forces and to determine the more stressed parts of the structure.

Multibody models, adopting just lumped stiffness elements, are complementary to finite element models and experimental campaigns.

This paper presents the results of a research activity aiming at integrating finite element modelling techniques and multibody approaches. The capabilities of Dassault Systèmes Simulia/Abaqus Explicit have been exploited thanks to the opportunity to integrate multibody as well as finite element models, exploiting the available element libraries and allowing to attribute a prescribed response to components.

## VALIDATION OF THE ANTHROPOMORPHIC TEST DEVICE

The anthropomorphic test device has been modelled modifying an existing finite element model of a dummy representative of a HYBRID III anthropomorphic test device used to perform experimental tests. Some parts of the dummy model have been considered as rigid, some others have been regarded to as deformable. The possibility to associate rigid bodies with lumped inertial characteristics to a mesh of rigid elements, capable to interact with the surrounding rigid or deformable bodies by means of contact interactions, allows for an accurate representation of the external geometry of the bodies involved in contact interactions, even if the parts are considered as rigid.

To validate the response of the dummy, different impact scenarios have been considered: namely two tests considering the impact conditions prescribed by the certification rules [15-18] with a rigid seat and two- and four- point restraint systems and the same impact condition considering an aeronautical seat provided with an energy absorbing device.

The numerical results are compared to the experimental evidences of the tests performed during the HeliSafe European Project [19-20].

The impacts performed considering a rigid seat allow for pointing out the behaviour of the anthropomorphic test device in itself, disregarding the deformation of the surrounding structure.

The ideally rigid seat is modelled using a 30 mm thick steel rig, mounted on a sled and imposing a triangular deceleration profile as prescribed by the certification rules of horizontal seats (horizontal deceleration with a peak of 30 g at 0.031 s, seat installed rotated at 60° nose up around the rotorcraft pitch axis).

Seat belts are modelled using monodimensional elements and are connected to the frame of the seat by means of springs in order to introduce preloads. The material characteristics have been derived from the results of experimental tests [21].

The model of the dummy has been derived from an available finite element HYBRID III 50th percentile male test dummy [22] and further developed at the Dipartimento di Ingegneria Aerospaziale of Politecnico di Milano [23-25]. The internal part of the thorax and of the vertebral column, especially the lumbar part, have been modified to be consistent with the prescription in the aeronautical field [26]. The lumbar load is straight and a sensor has been introduced in order to evaluate the lumbar load. As a matter of fact the lumbar load is a very important index to evaluate the severity of the impact.

The hybrid finite element/multibody model of the anthropomorphic test device has been developed converting into rigid bodies most of the body segments, retaining the finite element meshes to better represent the contact surfaces. The local deformability of the parts has been represented tuning pressure vs. overclosure contact laws between rigid bodies [27-29]. By means of this approach the number of the parts modelled as deformable is reduced, diminishing the subsequent computational costs.

The inertia properties of the different parts of the model have been attributed to the rigid bodies in order to correctly reproduce the characteristics of the HYBRID III body segments. Mass and inertia properties have been associated to a reference node (usually the center of gravity) of the rigid body.

Finite element modelling technique is used if the adoption of contact algorithm to represent the experimental response is inadequate or numerical problems arise due to large interpenetrations.

For this reason, the lumbar spine is not modelled using a generalized constitutive law in order to have a better representation of the history of the lumbar spine load.

To correctly reproduce the contact between the pelvic area and the seat, the buttocks have been modelled using finite elements characterized using a hyperelastic material.

The contact between the pelvic area and the seat is fundamental in the transmission of the vertical load to the anthropomorphic test device.

The connections between the different parts of the anthropomorphic test device are modelled using lumped parameters connection elements available in Dassault Systèmes Simulia/Abaqus Explicit code.

Connector elements are used to model articulations and are implemented defining constraint equations between the degrees of freedom of the different parts of the model. These elements allow for imposing constraints to represent the relative motion of the components with respect to each other. Generalised force vs. displacement (or velocity) relationship can be defined, as well as stops and failures. Torsional springs are used to introduce the proper stiffness.

The muscle activation has not been considered and the passive behaviour of the muscle can be modelled by means of joint resistance torques. Penalty torques prevent for infeasible movements between adjacent segments.

Contact between the different surfaces of the anthropomorphic test device, the seat pan and the seat rest are modelled using properly defined pressure vs. overclosure relationships. The contact curves have been calibrated performing sensitivity studies on the lumbar load attempting to obtain the best correlation between the numerical analyses and the experimental evidences.

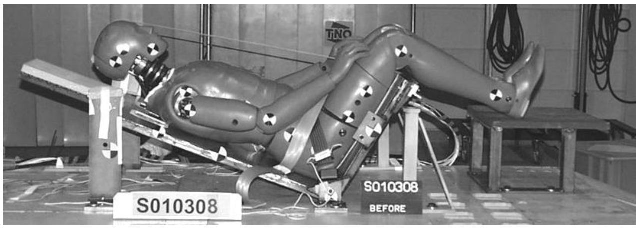



Figure 1 - ATD with two-point restraint system on the sled

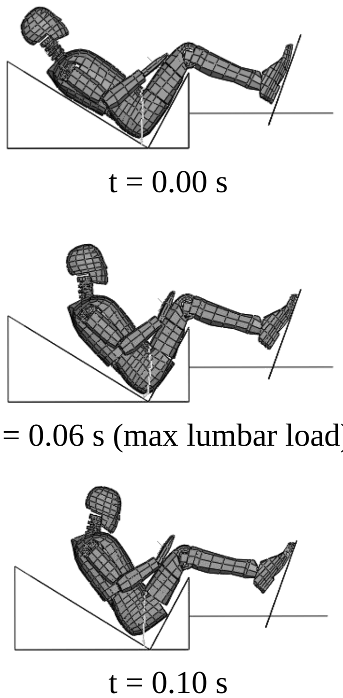



Figure 2 - Frames from the numerical analysis performed considering the hybrid model of the ATD, a rigid seat model and a two-point restraint system

Figure 1 shows the experimental set up of the test considering a rigid rig and the HYBRID III anthropomorphic test device while Figure 2 presents some frames of the numerical analysis.

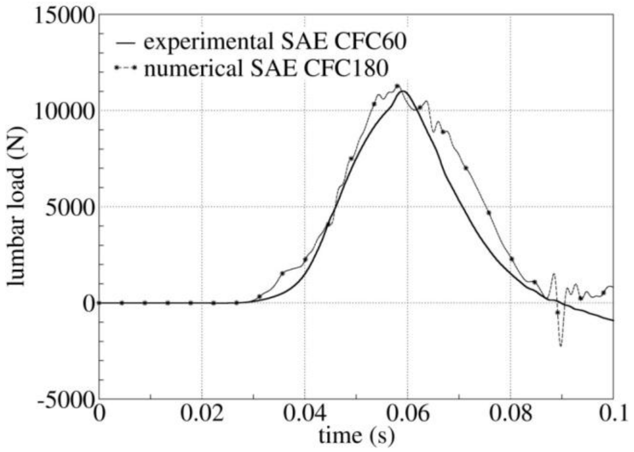



Figure 3 - Experimental-numerical correlation of the lumbar load using a rigid seat model and a two-point restraint system

Figure 3 presents the experimental vs. numerical correlation in terms of the time history of the lumbar load.

Similarly, an experimental vs. numerical correlation (Figure 4) has been performed considering the rigid rig and a four-point restraint system.

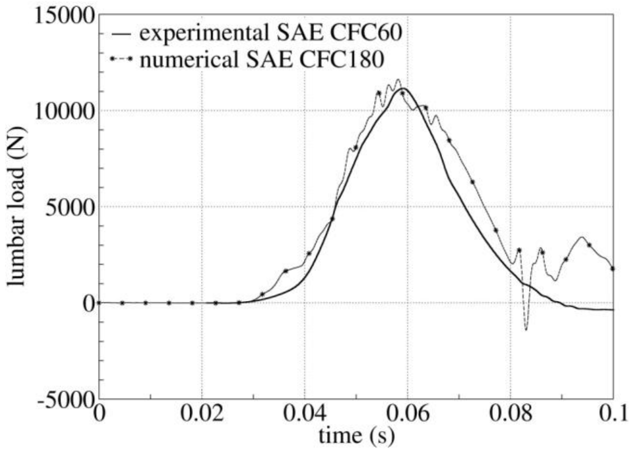



Figure 4 - Experimental-numerical correlation of the lumbar load using a rigid seat model and a four-point restraint system

As it can be seen in Figure 3 and in Figure 4, the experimental vs. numerical correlations are fairly good and the lumbar load time history and in particular the maximum load are well reproduced considering an ideally rigid seat with two- as well as four- point restraint systems.

The modelling technique used allows for a considerable saving in the computational costs. An analysis having 0.125 s of duration is completed in about 15 minutes using a single processor of an Intel Core i7 870@2.93 GHz, with 8 GB RAM.

## A PURE VERTICAL IMPACT SCENARIO CONSIDERING AN HELICOPTER SEAT AND A SUBFLOOR PORTION

The so validated model has been used to perform numerical analyses to evaluate the consequences of the impact considering an helicopter seat provided with an energy absorbing device and a subfloor portion in a pure vertical impact. The experimental setup is presented in Figure 5.

Figure 5 - Experimental set up of a pure vertical drop test

Even though pure vertical impact conditions are not prescribed by certification rules that refers to the seat only, the study of such an impact condition can provide important information about the interactions between different energy absorbing systems and the effects on the biomechanics of the anthropomorphic test device.

The test has been performed considering a vertical velocity of 8 m/s, a certified aeronautical seat provided with energy absorbing devices and with four-point restraint seatbelts, a HYBRID III anthropomorphic test device, a subfloor portion and ballasts placed in proper position in order to grant a flat impact to the ground and to represent the masses located close to the considered subfloor portion insisting on the same structural elements.

The energy absorbing devices commonly installed on seats have a typical force vs. displacement curve characterized by a steep increase in the load that then tends to remain almost constant in order to maximize the area under the curve, related to the absorbed energy.

Such a functioning curve can be achieved considering an energy absorber made with a metallic tube drawn through dies which flattens it. The reverse motion is prevented by a blocking system.

The subfloor structure considered is representative of a subfloor portion. It is made of two metallic panels representing the helicopter floor and the outer skin, respectively, supported by a frame of stringers. The upper and the lower skins are connected by transversal and longitudinal beams. In impacts with a significant vertical velocity component, the beam webs and the intersection elements between the longitudinal and the transversal beams can be exploited as energy absorbing elements, interposed between the upper and the lower beam flanges, respectively connected to the outer skin and to the floor. Such elements need to be carefully designed because they can represent high strength points causing the transmission of high loads to the occupants and preventing the remaining parts of the structure from collapsing during the energy absorbing process.

In the considered configuration (Figure 6), four Al 2024-T3 intersection elements have been placed in correspondence of the corners. Intersection elements consist of four angled elements, creating a closed square section having one diagonal delimited by the subfloor longitudinal web beam and the other by the transversal web beam. These elements, designed to collapse at a given force level, are supposed to plastically deform so to absorb energy during the impact phases.

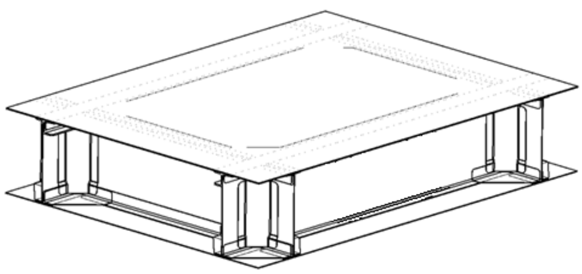


Figure 6 - Scheme of a typical subfloor portion

Experimental tests have been performed to evaluate the energy absorbing capabilities of the single intersection elements. In particular the force vs. displacement curves have been considered.

Figure 7 presents a typical configuration of an intersection element before and after being crushed using a vertical drop tower while Figure 8 reports the adimensional force vs. displacement curve recorded during the test. This curve has been obtained dividing the force by the maximum initial peak value.

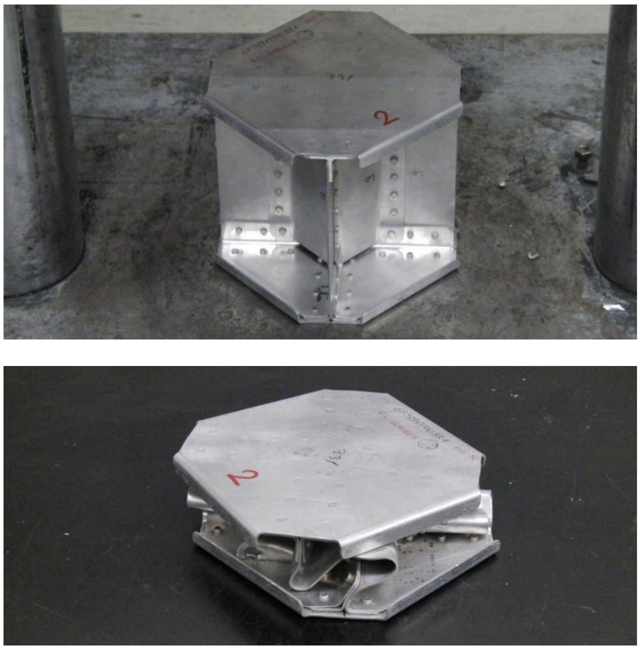


Figure 7 - A typical intersection element before (top) and after (bottom) a crash test performed using a vertical drop tower

Extensive experimental campaigns have been performed on intersection elements and subfloor subcomponents. The results pointed out that, considering a given geometry and varying the thickness of the specimens, the overall shape of the force vs. displacement curve is almost unaltered while the magnitude of the force does differ [30].

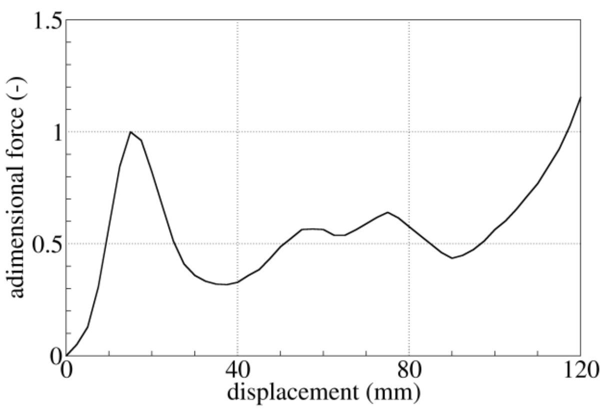



Figure 8 - A typical experimental force vs. displacement curve for an intersection element (the force has been adimensionalised w.r.t. the initial peak value)

The aeronautical seat is modelled considering two rigid bodies: one is fixed to the floor, the moveable part, representing the seat bucket and the fixtures of the seat belts, is allowed to slide with respect to the struts by means of translational joints. The energy absorbing device is interposed between the fixed and the moveable part and it is modelled by means of a beam and a slack spring in parallel. The beam models the structural response of the shock absorber while the non linear spring allows for considering the bottoming out of the seat after having performed the maximum available stroke.

The hybrid modeling technique has been applied also to the subfloor: the intersection elements have been introduced in the model in a fashion similar to that adopted for the seat energy absorbing device. The experimental force vs. deformation curve of such element has been attributed to a lumped parameter model made of a beam element and of a non linear spring element used to reproduce the bottoming out of the element.

During the vertical drop test the intersection elements did not perform the complete stroke available and the subfloor structure did not significantly contribute to absorb energy (Figure 9).

As it can be seen in Figure 10 and in Figure 11, the fore elements (w.r.t. the seat) shortened of about 25% respect the initial length, the aft ones of about 12.5%. The energy absorption capabilities of the beam webs was just partially used and these parts did not severely crush due to the excessive strength of the intersection elements.

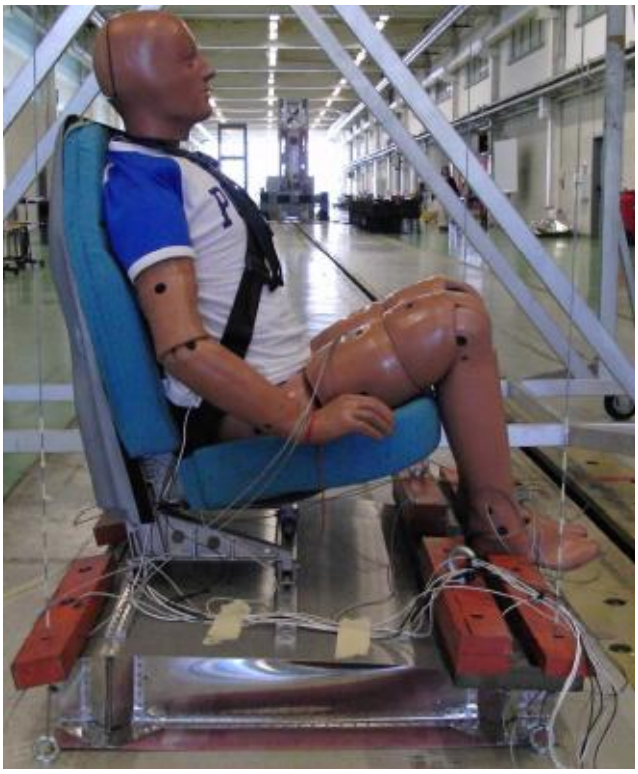


Figure 9 - Assembly (subfloor, seat and anthropomorphic test device) after the vertical drop down test performed at 8 m/s

Figure 10 - Fore left intersection element after a vertical drop down test performed at 8 m/s

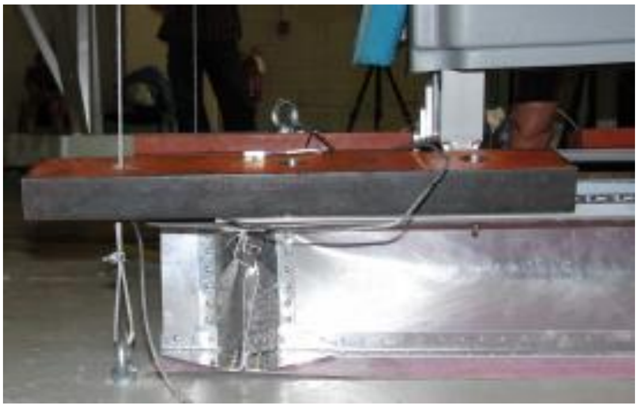
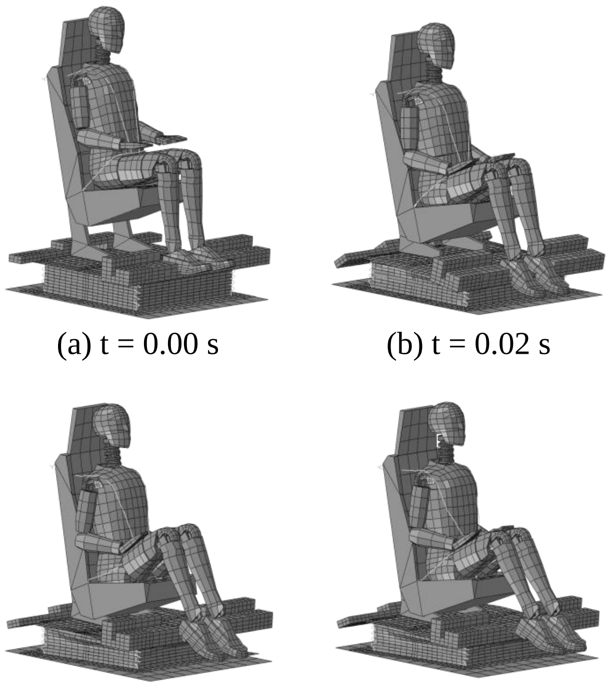


Figure 11 - Aft left intersection element after a vertical drop down test performed at 8 m/s

Due to the little exploitation of the available stroke of the intersection elements and of the subfloor structure, the most of the energy absorption has been demanded to the device installed on the seat.

Being that the typical functioning curve (force vs. displacement) of the energy absorbing device installed on the seat is not available, sensitivity analyses have been performed considering an elastic-perfectly plastic response of the absorber and different values of activation force.

The comparison of the results have been performed qualitatively and in terms of lumbar load time history.



(a) t = 0.00 s (b) t = 0.02 s

(c) t = 0.04 s (d) t = 0.08 s

Figure 12 - Sequence taken from an analysis of vertical impact

Figure 12 presents some frames of the numerical analysis demonstrating a good agreement between the experimental evidences and the results of the numerical analyses. In the numerical analysis, as in the vertical drop test, the fore intersection elements result more compressed than the aft ones and the lateral skin appears slightly curved.

As far as the comparison of the lumbar load is concerned, Figure 13 presents the results obtained considering different values of the activation force of the energy absorbing device of the seat. The initial phase of the impact (up to t = 0.02 s) is driven by the energy absorption contribution of the upper sandwich panel. The central phase of the impact, until t = 0.035 s, represents the phase in which the upper part of the seat moves activating the energy absorbing device, until all the available stroke is exploited. The bottoming out of the seat is represented by the sudden steep increase in the lumbar load.

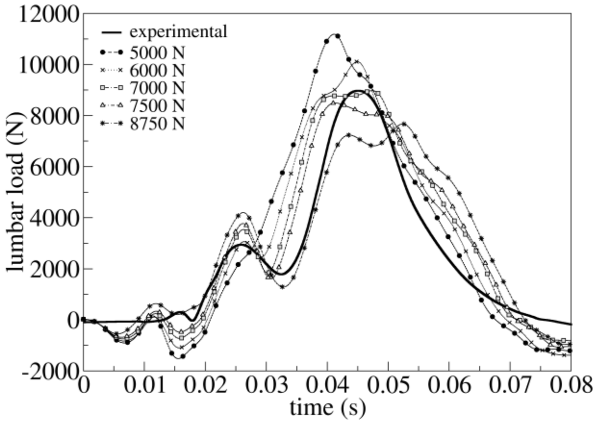



Figure 13 - Lumbar load time history: experimental vs. numerical curve for different activation force values of the energy absorbing device of the seat

According to the sensitivity analysis performed, the higher the activation force of the energy absorbing device of the seat is, the higher the lumbar load is, until the bottoming out of the seat. The slope of the curve after the bottoming out is correctly reproduced, but the magnitude of the lumbar load after the complete exploitation of the stroke of the seat is hardly obtained.

The difficulties in correctly reproducing the magnitude of the lumbar load are due to many factors such as the modeling of the material reproducing the flash of the ATD, the complex pressure vs. overclosure laws between the body segments and the seat, the interactions between the different energy absorbing systems (in particular the intersection elements and the energy absorbing device of the seat) and the structure.

Nevertheless, the hybrid multibody/finite element technique proved to be capable to reproduce the overall behavior experienced during the vertical drop test and to fairly reproduce the lumbar load time history considering the high dependence on the activation force of the energy absorbing device of the seat. The computational cost is very limited (about 15 minutes to complete a 0.08 s analysis, using a single processor of an Intel Core i7 870@2.93 GHz, with 8 GB RAM).

## CONCLUSIONS

The hybrid multibody/finite element modelling technique presented in this work and validated in some reference cases have been applied to a more complex scenario considering the vertical impact of a helicopter subfloor portion. The overall behaviour of the structure, of the aeronautical seat and of the anthropomorphic test device has been correctly reproduced. Considering the reduced computational costs, this technique turns out to be especially suitable to analyse the structural response of parameterized models, to compare different topological architectures and to perform numerical optimizations during all the phases of the design process, with different detail levels. Moreover this approach allows for considering different impact conditions, accounting for different attitudes, soils and components of velocity. It is also interesting noticing the possibility to switch a part from multibody to finite element in order to obtain a more detailed response considering the presence of the remaining structural parts.

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