Analysis of a crashworthy sled test for light certified Aircrafts

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The Certification Specification for light aircrafts (CS-23) fixed by European Aviation Safety Agency (EASA), specifically Parts 23.561 and 23.562 about the "Emergency Landing Conditions", requires for crashworthy evaluation of seats in a dynamic environment, that each seat/restraint system, successfully complete two dynamic tests. About that, computer simulations provide an important mean in support to design, since these tools produce detailed predictions about the performances and the most critical aspects of every tested solution, directing the execution of full-scale dynamic tests only to suitable configurations. The activity presented in this paper is about the simulation, with a non-linear Finite Element analysis, of crashworthy dynamic tests applied to a two seat light aircraft with the aim to calculate the magnitude of the loads acting on the occupants during an emergency landing, so to verify the compliance with the requirements. The aircraft under study has a Maximum Takeoff Weight of 750 Kg and a stall speed of 45 KCAS, and is characterized by two seats integrated in a fuselage completely made in composite materials. This configuration can be advantageous about weight reduction, but the lack of space below the seats, prevents the installation of energy absorbing devices, and so, most of the role of load attenuation competes to seat cushions and restraints, that could be not sufficient to comply the specific requirements. The analysis were performed using the solver LS-DYNA® and the model was generated through the pre/postprocessor LS-PREPOST®, reproducing the test conditions specified in regulations: Forward test, simulating a predominant impact along the longitudinal axis with a peak value of deceleration of 26g; Down test, simulating a predominant impact along the vertical direction, with a peak value of deceleration of 19g. The observation of the results, put in evidence that the "critic scenario" revealed to be vertical impact, in particular the lumbar force acting on the occupant of the rear seat, that resulted above the fixed limits.

I. Introduction

The concept of safety can be seen by two different perspectives: the control and the containment of the causes that lead to an accident; the control and the containment of the causes of injuries and fatalities occurring during accidents. The design according to the principles of Crashworthiness is just the realization of this second idea. Crashworthiness is a very challenging matter in Light Aircrafts development, and even more, in that airplanes which, as the one analysed in this study, are characterized by seats directly integrated in the fuselage. In fact, while this solution can be advantageous about weight reduction, thanks to the absence of a supporting structure to the seats, on the other hand, the lack of space below the seating system, prevents the installation of energy absorbing devices, that couldn't find enough space neither in the subfloor, that in small light aircrafts, is often entirely occupied by other systems. It's so evident that most of the role of load attenuation competes to seat cushions and restraints, and could be not sufficient. It's so necessary, in the development of the design phase, to consider different solutions that could permit to obtain an adequate level of human protection, so to comply the specific requirements. About that, computer simulations provide an important mean in support to the design, since these tools produce detailed predictions about the performances and the most critical aspects of every analysed solution, directing the execution of full-scale dynamic tests only to suitable configurations. This has led to a considerable restriction of time consumption and costs. In particular, Finite Element Analysis techniques and applications became a consolidated design tool in predicting dynamic events in aircraft seats industries. The attention of the authorities and the industries has been on the development of more and more reliable methods of simulation to permit the application of computer modeling not only in support of dynamic testing but, in some circumstances, also in lieu of it, realizing the so called "certification by analysis", through the generation of validated numerical models[1]. This paper describes the application of a Finite Element dynamic simulation to a two-seats tandem light aircraft, with a Maximum Take-Off Weight of 750 kg and a stall speed of 45 KCAS. This aircraft was originally certified as a Very Light Aircraft, in compliance with the requirements fixed in the regulations CS-VLA by the European Aviation Safety Agency (EASA), where dynamic crash tests are not mandatory. The aim of the manufacturer was to obtain certification for this airplane for category CS-23, and in this case, it is necessary for each seat/restraint system to successfully complete full-scale dynamic tests or to demonstrate the compliance with the requirements by a rational analysis supported by dynamic tests. In order to verify the respect of the load limits fixed by the regulations, and so the possibility to pass full-scale tests, two dynamic simulation have been conducted on a Finite Element model of the aircraft, reproducing the test cases exposed in CS-23.562. The analysis have been conducted using the software LS-DYNA®, that is an explicit finite element code, delivered by Livermore Software Technology Corporation, widely used to investigate the non-linear dynamic response of three-dimensional structure, particularly suitable to the study of phenomena that evolves very quickly in the time, as crashes. It applies the Central Difference Method for the time integration, with a time step variable in the time in function of the change in the dimensions of the element defined in the model.

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II. Crashworthiness in regulations

The reference regulations for light aircrafts certification in European Union is CS-23, issued by EASA. In its original version, it was applied to: "*Aeroplanes in the normal, utility and aerobatic categories that have a seating configuration, excluding the pilot seat(s), of nine or fewer and a maximum certificated take-off weight of 5670 Kg (12 500 lb) or less; and Propeller-driven twin-engined aeroplanes in the commuter category that have a seating configuration, excluding the pilot seat(s), of nineteen or fewer and a maximum certificated take-off weight of 8618 Kg (19 000 lb) or less*".[2] This regulation has recently been updated by EASA trough the "Amendment 5" that extends the limits of the normal category aeroplanes to 19 or less passengers' seating and a maximum certified take-off mass of 8618 Kg or less[3]. The sections that pose the attention on the theme of crashworthiness are 23.561, 23.562 and 23.785. The first two of that deal with the problem of "Emergency landing conditions", in particular, in the first part, static requirements are exposed, while the second one is dedicated to dynamic requirements. Section 23.785 is specifically dedicated to the design of seats and restraint systems. The main criterion that led to the definition of these requirements is that each occupant of the aircraft, must be protected in emergency landing conditions, and the structure has to be designed with the objective to permit to the passenger to escape, with a reasonable possibility, serious injuries even if it results heavily damaged. This target can be obtained with a "*proper use of seats, safety belts and shoulder harness*".

CS 23.561 – General In section 23.561 are exposed the static ultimate load factors of the inertia loads that the occupant can suffer without being subjected to serious injuries, and the ultimate load factors to apply to the items of mass that could injure an occupant within the cabin.

LOAD DIRECTION	**Normal Utility and Commuter Airplanes [g]**	**Aerobatic Airplanes [g]**	**Items of Mass [g]**
Upward	3.0	4.5	3.0
Forward	9.0	9.0	18.0
Sideward	1.5	1.5	4.5
Downward	6.0	6.0	/

Table 1 Load factors specified in CS 23.561

In this section are also specified the design loads to be used when considering a landing with a retracted landing gear; the aircraft has to be dimensioned to protect the occupants also in the eventuality of this type of landings, considering a downward inertia force of 3 g and a friction coefficient at the ground of 0.5. The structure must be designed to protect the occupants even in case of a complete turnover.

CS 23.562 – Emergency Landing Dynamic Conditions. This section specifies the standards to apply in the design and the testing phases of seats and restraint systems. According to the regulations, each seat/restraint system has to successfully complete two dynamic tests, or demonstrate the respect of the conditions required through a rational analysis supported by dynamic tests. These tests are performed simulating the presence of the occupants by the usage of certified Anthropomorphic Test Devices (ATD)[4]. The target of the tests is to verify structural integrity and to prove the compliance to the requirements of human tolerance to injury expressed in the regulations. The tests required are two:

- Test 1: simulates an emergency landing with a principally vertical impact. Regulations require that: "*the change in velocity may not be less than 9.4 m (31 ft) per second. The seat/restraint system must be oriented in its nominal position with respect to the aeroplane and with the horizontal plane of the aeroplane pitched up 60°, with no yaw, relative to the impact vector. For seat/restraint systems to be installed in the first row of the aeroplane, peak deceleration must occur in not more than 0.05 seconds after impact and must reach a minimum of 19g. For all other seat/restraint systems, peak deceleration must occur in not more than 0.06 seconds after impact and must reach a minimum of 15g*". This test may appear to simulate a nose down accident, but it reproduces an essentially flat impact, with high sink-rate, into a surface that has a 0.5 coefficient of friction.
- Test 2: simulates an emergency landing with a predominant horizontal impact. "*For the second test, the change in velocity may not be less than 12.8 m (42 ft) per second. The seat/restraint system must be oriented in its nominal position with respect to the aeroplane and with the vertical plane of the aeroplane yawed 10°, with no pitch, relative to the impact vector in a direction that results in the greatest load on the shoulder harness. For seat/restraint systems to be installed in the first row of the aeroplane, peak deceleration must occur in not more than 0.05 seconds after impact and must reach a minimum of 26g. For all other seat/restraint systems, peak deceleration must occur in not more than 0.06 seconds after impact and must reach a minimum of 21g*". To take in account floor deformation resulting from the impact, a pitch angle is assigned to one of the floor rails used to attach the seat/restraint system to the airframe, and a roll angle of 10 degrees is imposed to the other one.

The target of dynamic tests is the compliance with the requirements of structural integrity and human tolerance to injury exposed as follows**:**

- The seat/restraint system must restrain the ATD even if it may be subjected to damages and deformations
- All the attachments of the restraints must remain intact and all the elements of the restraints must remain in a correct position on the ATD during the test
- The occupant must be protected from serious head injury; the value of HIC must not exceed 1000
- Loads measured in individual shoulder harness strap, may not exceed 794 kg (1750 lb); while in dual strap the ultimate value is 907 kg (2000 lb)
- The compression load measured between the pelvis and the lumbar spine of the ATD may not exceed 680 kg (1500 lb)

CS 23.785 – Seats, berths, litters, safety belts and shoulder harness. This section provides the requirements to be satisfied in the design of seats and restraint systems. Each system may be designed to support an occupant weighing at least 98 kg (215 lb) when subjected to the ultimate load factors assigned in regulations. Each restraint system must consist of a seat, a safety belt and shoulder harness with a metal-to-metal latching device that must supply levels of protection in line with the provision of section 23.562 of the regulations. Each restraint system must have a single-point release in order to facilitate the occupant evacuation in case of emergency, and must be designed to permit to all the crew members to perform all their actions and may have blocking systems so that they don't interfere with the operations and the fast egress from the airplane, when not in use. The cabin structure surrounding each seat, including the internal walls, the instrumentation, and each item within the striking distance of the occupant's head or torso, must be free of potentially injurious objects. If energy-absorbing devices are in usage, the compliance with the requirements exposed in sections 23.561 e 23.562 may be demonstrated.

The central role of seats in humans' protection from impacts is evident, since they represent the interface between the occupant and the structure so, even more for light aircrafts, are a crucial element in the transmission of the loads and, as consequence, in the design according to the principles of crashworthiness. Seats must be at the same time:

- Resistant: they have to support the loads due to the occupants and to external circumstances; in particular they must preserve an intact structure in case of a crash, so not to be a possible source of injury;
- Lightweight: they don't have to load excessively the structure and require a growth of the primary components ad so an increase of the total weight of the aircraft
- Comfortable: the occupant should feel a sense of comfort and relax and maintain a correct position and the possibility of moving
- Energy Absorbing: seats must be designed to absorb a certain quantity of energy, so to maintain the transmitted loads below the limits of human tolerance to injury in the case of impacts.

III. Modelling

Starting from the CAD model of the aircraft, provided by the manufacturer, a Finite Element model for the analysis with the solver LS-DYNA has been defined. This code receives an input file with extension ".k", organized in a series of "cards" that contain the necessary information to build model and the parameters of the analysis. The cards are grouped in a series of data blocks, identified by "keywords"[5]. For the model generation and the analysis of the results, the software for pre/post processing, LS-PREPOST, has been in use.

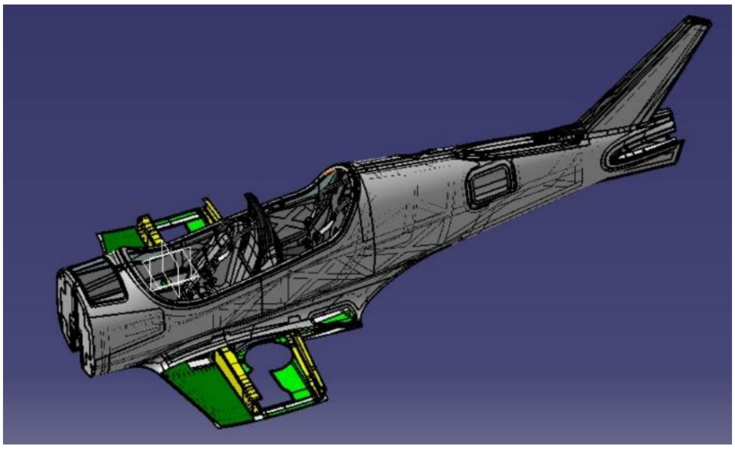

Figure 1 CAD model of the aircraft

Since the target of the analysis was the check of the compliance with human tolerance to injury criteria by the seats and the restraint system, and the determination of the possible strikes of the occupants inside the habitable space, as consequence of the impact loads, for FE modelling a partial section of the fuselage has been considered, including seats, restraints and the structural elements that could intercept the trajectory of the dummies during the crash events. From the CAD model has been possible to relieve that the structure is all made by different layers of composite materials whose observable properties have been reassumed in Table 2.

	FABRIC	UNIDIRECTIONAL	FOAM
$\boldsymbol{E_A}$	55 [GPa]	1.2 [GPa]	0.5 [GPa]
$\boldsymbol{E_B}$	55 [GPa]	1.2 [GPa]	0.5 [GPa]
$\boldsymbol{\nu_{AB}}$	0.4	0.4	0.25
$\boldsymbol{G_{AB}}$	4.2 [GPa]	4.2 [GPa]	0.2 [GPa]
$\boldsymbol{G_{BC}}$	2.9 [GPa]	2.9 [GPa]	0.2 [GPa]
$\boldsymbol{G_{AC}}$	2.9 [GPa]	2.9 [GPa]	0.2 [GPa]
ρ	1.6 [kg/mm^3]	1.6 [kg/mm^3]	0.8 [kg/mm^3]
h	0.218 [mm]	0.15 [mm]	variable

Table 2 Table of Materials relieved in the structure

$\mathbf{E_i}$ = Elastic Modulus in i direction; $\boldsymbol{\nu_{ij}}$ = Poisson Ratio in ij direction; $\mathbf{G_{ij}}$ = Shear Modulus in ij direction; **ρ** = Material density; **h** = Ply thickness

However, in crashworthiness applications, especially in the realization of energy absorbing devices, it is necessary to bring the materials to work in the plastic range of their stress-strain curve and so, to operate in a zone of controlled deformations; for this purpose, a complete knowledge of their elastic-plastic behavior is required. To generate validable Finite Element models, a complete characterization of the materials curves should be obtained through a significant amount of static and dynamic tests, defining properties as yielding strength, hardening parameters, ultimate strength, effective plastic strain, so to be able to simulate, in a realistic way, the three-dimensional behavior of each component, included non-structural elements as seats and belts, whose stress-strain relation is highly nonlinear[6]. In the case in study, the amount of data provided by the aircraft manufacturer was not enough for a complete definition of the materials and it hasn't been possible to perform the appropriate tests on the components, and so, for a complete characterization of the properties to assign to the model of seat cushions and seat belts, it has been necessary to consult the data sheet of the materials available in bibliography.

Structure. The structure has completely been modeled with 2D shell elements of the type "CQUAD4". The materials have been defined through the block *MAT_COMPOSITE_DAMAGE and are that extracted from the CAD model and reassumed in the table above. The failure criterion contemplated by this material model, is the one proposed by Chang-Chang[7-8]. Layers in composites have been created using the specific block *PART_COMPOSITE useful to generate laminate components with plies of different materials and orientations.

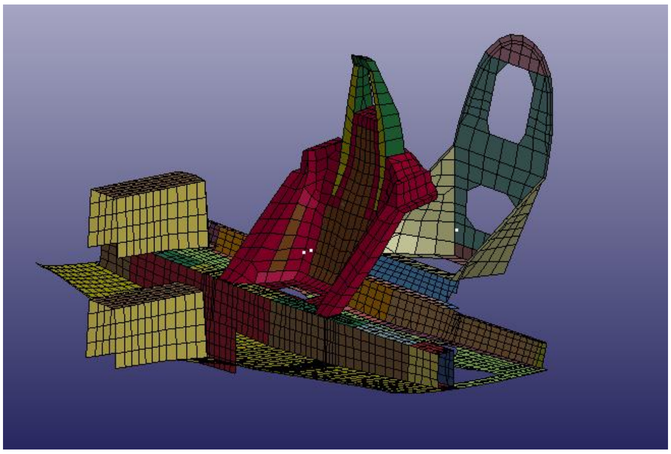

Figure 2 Finite Elements model of the structure

Seat cushions. To improve the energy absorption performances of the seats, a bottom cushion has been inserted into the model. This device, especially for configurations as this one is, characterized by seats directly integrated in the fuselage, plays a central role in human protection from injuries, in the case of vertical emergency landing conditions, where high loads are applied on the occupants' spinal column. Its design is a not easy problem in the application of crashworthiness criteria, because it's necessary to reach a compromise between an adequate level of comfort offered to the occupant, and a high level of energy absorption so that the transmitted loads in case of an impact, stand below the limits of human tolerance to injury. In general, a comfortable cushion could be thicker and softer, but the risk is to emphasize the phenomenon of dynamic overshoot and to increase the loads acting on the spinal column of the occupant[9]. A design strategy aimed to reduce the thickness, preserving the comfort perceived, could be the production of a shaped cushion that follows the shape of the bottom of the occupant; this solution not only reduces the possibility of dynamic overshoot, but also ensures a major contact area with the human body. Energy absorption properties can be provided by the usage of crushable materials as, for example, friable polyurethane foams. Another possibility is the use of rate sensitive foams that results useful both for crashworthiness and for comfort because, this kind of materials deforms slowly to ensure comfort, while become harder in case of fast loading excursions, contributing to a growth in absorbed energy and a reduction of dynamic overshoot[10].

Foams are substances formed by trapping pockets of gas in liquids or solids and are utilized in a big variety of applications, as energy absorption and comfort. Their versatility mostly depends from the material of the matrix and the morphology of the gas phase. It can be possible to distinguish two kinds of morphology: open-cell and closed-cell. In closed-cell foams, the gas forms discrete pockets, each of that completely surrounded by the solid material. In open-cell foams, the gas pockets are connected to each other. Matrix can be made of rigid or flexible materials. Managing the ratio between open and closed cells is possible to regulate the elastic features of the materials according to the desired performances. Foams are designed to sustain compression loads; generally, they do not show efficient resistance to shear or tensile forces. The typical behavior in compression of the foams used for the production of cushions in aeronautical applications is that shown in Figure 3.

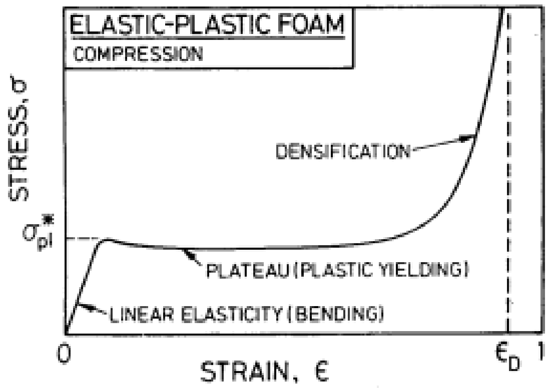

Figure 3 Typical shape of the characterization curve of compressed foams[1]

On this curve is possible to observe three characteristic zones: an initial region of linear elasticity; a plateau region (that can show a growth of the strength with the increase of the deformation); and a densification region. The initial elastic region presents a stiffness due to the resistance of the material of the matrix and, in general, for this kind of materials is small. The plateau region extends for most of the strain axes on the stress-strain curve. When the walls of the cells fail, the gas is solicited; in open-cell foams, it exits from the open porosity, while in closed-cell foams, it remains compressed in the cells. Compression can be strong enough to break the walls of the cells, and so the gas is released in the atmosphere, with a permanent lack of recovery of the initial shape. If the matrix is strong, the cells can remain intact, but completely collapse. When the cells collapse or fail, the densification phase begins. Densification strain, ε_D, is defined as the strain value at which the stress has an asymptotic shape. Most of the foams follow this behavior, with the three zone that assume different dimensions according to the matrix and the morphology of the cells. The drawback of these materials is that they can be very sensitive to external factors as temperature and humidity, and is so necessary to protect them from the decrease of their performances. In this application cushion has been modelled using 3D solid elements and its dimensions are: 440 mm x 440 mm x 116mm.

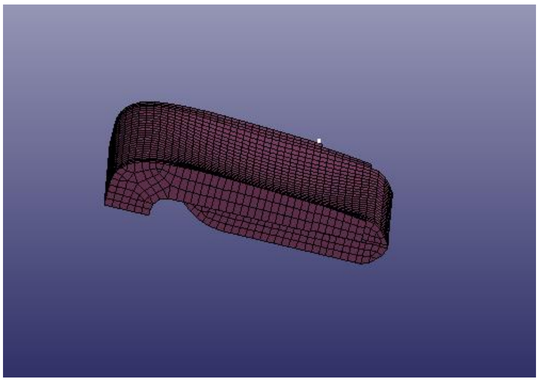

Figure 4 Finite Element Model of the cushion

The material selected for these analyses is polyurethane DAX foam, commonly in use in aircraft seats manufacturing, whose properties have been extracted by bibliographic references[11]. It has been implemented in LS-DYNA using the model *MAT_LOW_DENSITY_FOAM assigning, besides a density of 38 kg/m^3 and a Young Modulus of 0.5 kg/m^2 also the characterization curve of stress-strain.

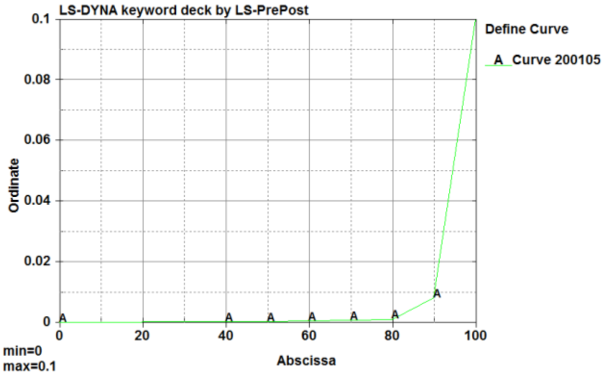

Figure 5 Stress-strain curve of the low-density foam

Along the vertical axis are reported the stress values in kN/mm^2; along the horizontal one, volumetric strain percentage. Besides the seat cushion, a back cushion and a head cushion are generally present. The backrest has an impact on what regards the comfort and the reduction of spinal loads because, providing a support for the back, helps to maintain a correct position; the headrest has the benefit of avoiding head impacts and whiplashes due to the hyperextension of the neck.

Belts. Restraint systems are fundamental in human protection during impact, and LS-DYNA provides efficient tools to model them in different configurations. The belts have been modelled using 1D SEATBELT elements, with 4 points of attachment directly connected to the fuselage structure. The material is polyester.

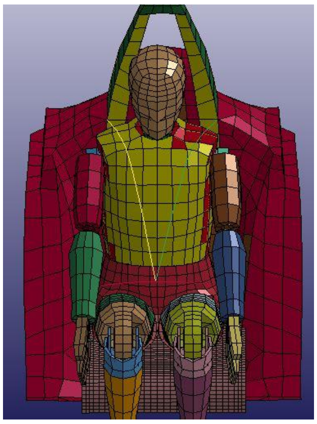

Figure 6 detail of the FE Model of the seat belts

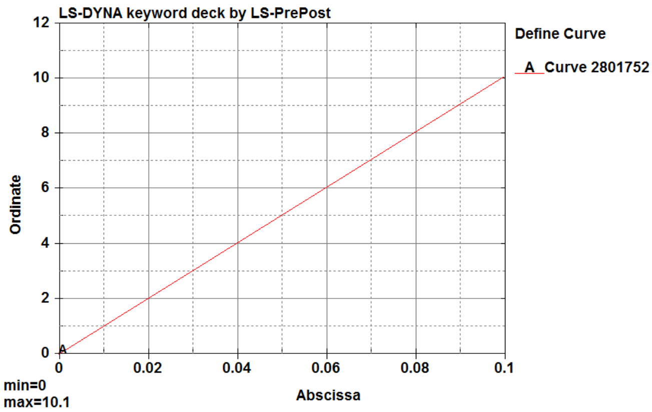

Figure 7 Force – Elongation curve of the belts

Loading and unloading force-elongation curves have been assigned to the model so to simulate the presence of a pretensioner and a retractor. For an applied force of 1000 Kgf, the belt stretches by 10%.

Dummies. In order to simulate the presence of two occupants on forward and rear seats, two Hybrid III dummies models have been in use, made by combinations of several spring, beam, shell and solid elements. It is evident from Figure 8 the different seating position of the dummies, due to available spaces.

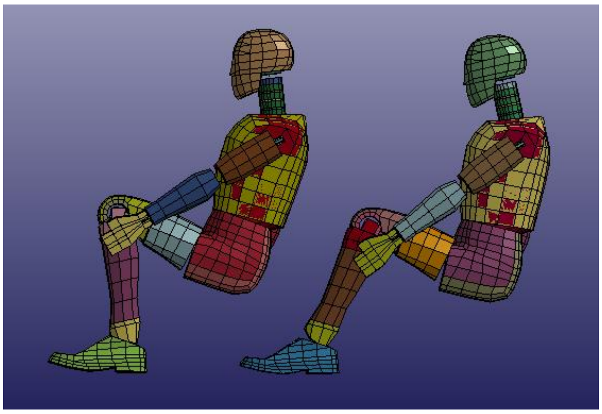

Figure 8 FE Model of the Hybrid III dummies

Contact algorithms have been defined to model the interactions between the occupants and the structure, the cushions and the belts, and also between the cushions and the structure, using the pre-defined card *CONTACT_AUTOMATIC. The purpose of each contact algorithm is to avoid the interpenetrations between surfaces during the time interval of the analysis. In crash analysis the deformations can be very large, and predetermination of where and how contact could take place, may be difficult or impossible. For this reason, LS-DYNA gives the opportunity to define “automatic” contacts, that are non-oriented, meaning that they can detect penetrations coming from either side of an element. One of the most commonly used algorithm for simulation of contacts is “penalty method”: in this method, springs of adequate stiffness and no mass are added between penetrating nodes and the opposite surface. The stiffness is determined so to result of the same magnitude of the less stiff element in the contact[12].

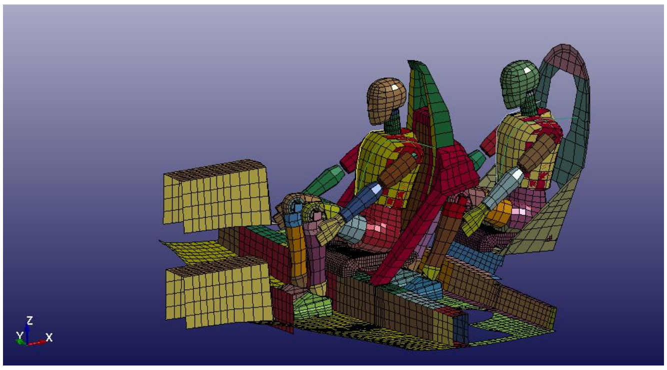

Figure 9 Complete FE Model

<u>Boundary conditions</u>. Once modeled all the elements, boundary conditions have been applied, so to simulate the development of the two dynamic tests, according to the directives contained in paragraph CS-23.562 of the regulations. First, the application to each element of loads due to gravitational acceleration has been simulated. Then, constraints to translation in lateral direction and to rotations have been imposed only to the structure, leaving the cushions, the belts and the dummies free to move, since the interest of the analysis is specifically directed to their dynamic behavior. Finally, different velocity and acceleration conditions have been applied, for the two test cases, as required by regulations:

- TEST 1: the modulus of the initial velocity, assigned to the entire model including cushions and dummies, is 10.4 m/s, with components along vertical and longitudinal directions, so to simulate the orientation of the aircraft, pitched up of 60° respect to the horizontal plane, as required by regulations, in which a change in velocity not less than 9.4 m per second is prescribed. A deceleration pulse, with a peak value of 19 g, has been applied only to the structure, to simulate the impact at the required conditions, so to observe the interaction between structures, dummies and cushions.
- TEST 2: the value of initial velocity assigned to the entire model is 14.1 m/s along the longitudinal direction, where the regulations require a change in velocity not less than 12.8 m per second. A deceleration pulse with a peak value of 26 g has been applied only to the structure, to simulate the impact at the required conditions.

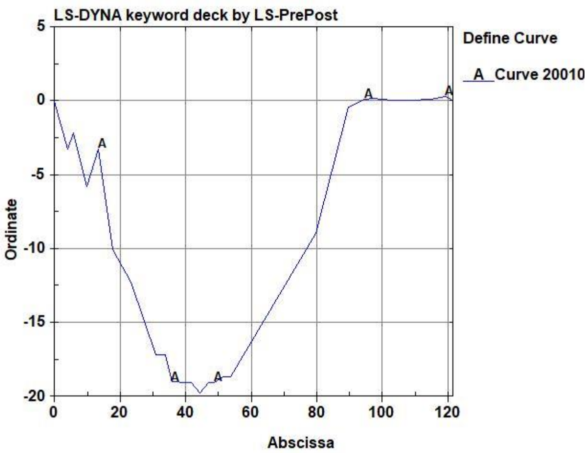

Figure 10 Deceleration pulse for TEST 1

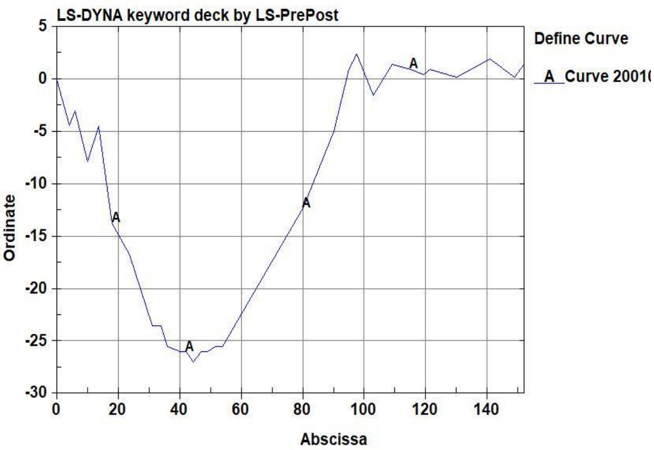

Figure 11 Deceleration pulse for TEST 2

The vertical axes indicates the acceleration values in ‘g’, clearly negative, while on the horizontal axes there is the time, expressed in milliseconds (ms). It is possible to observe that, according to the requirements, the peak occur in less than 0.05 s from the beginning of the impact. The time of the analysis is 120 ms for Test 1 and 150 ms for Test 2. During the analysis, time step, energy ratio and energy balance have been verified to control the accuracy of the process. Hourglass energy has been controlled using a stiffness-based algorithm. Hourglass modes are nonphysical, zero-energy modes of deformation that produce no stress. This phenomenon is due to the use in numerical integration of “reduced elements”; the integration is carried out only in a single point in the middle of the element. This lead to a saving in computational costs, but the accuracy of the solution can decrease.

IV. Results

TEST 1 Results In the case of Test 1, representative of a predominantly vertical impact, occupants are subjected to high loads acting primarily along the spinal column. The attention has been so focused on verifying the values of the loads applied to the lumbar region of the dummies. For this purpose, by using the postprocessor LS-PREPOST, from the output file “JNTFORC”, have been extracted the time evolutions of the z-forces applied to joints positioned between pelvic and lumbar regions of the two dummies.

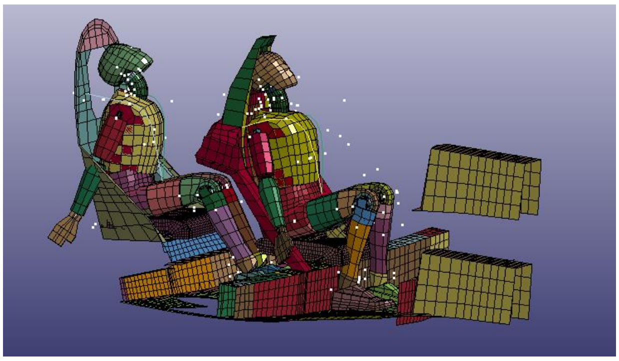

Figure 12 Detail of down impact

To observe the influence of the cushions material on the lumbar stresses applied to the dummies, the simulation of vertical impact, has been conducted at first modeling it with the elected material, DAX26 foam, and then with two other materials, DAX55 foam and a generic commercial open-cell Polyurethane foam, with a density of 27 Kg/m^3, whose properties have been extracted from bibliography and whose characterization curves are represented in Figure 13 below.

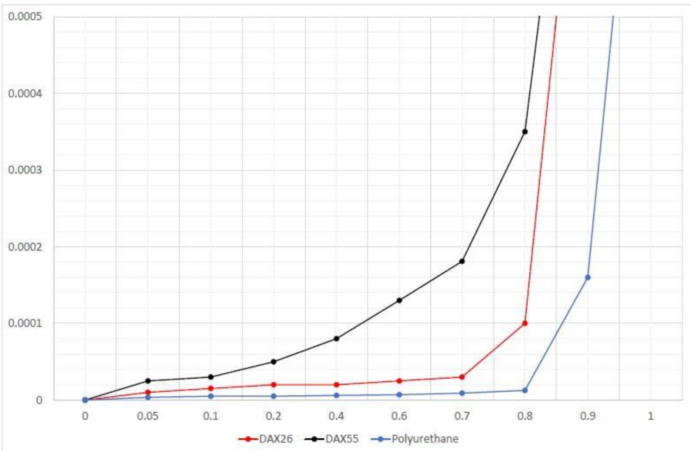

Figure 13 Stress-strain curves of the foams: DAX26 (red curve); DAX55 (black curve); generic Polyurethane foam (blue curve)

The red curve is representative of DAX26 foam, the black curve of DAX55 foam and the blue curve of the generic Polyurethane foam. Along the vertical axis are reported the stress values in kN/mm^2; along the horizontal one, volumetric strains. DAX55 foam is characterized by an anticipation of the densification phase, respect to DAX26 foam, while generic Polyurethan foam, has an higher densification strain. The results of the analyses can be red on Figure 14 and Figure 15 where on the horizontal axes there is the simulation time in ‘ms’,and on the vertical axes the z-force values measured in ‘kN’.

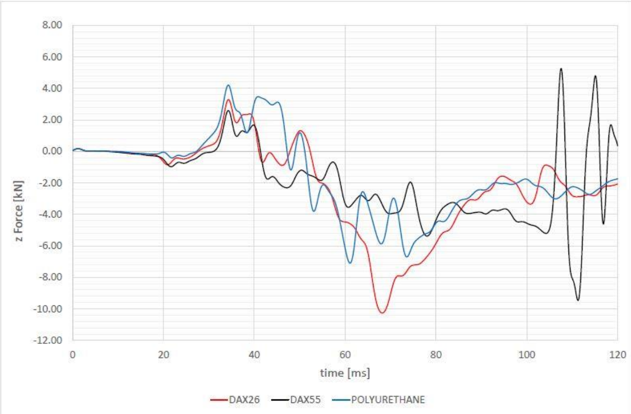

Figure 14 Lumbar forces acting on the occupant o forward seat

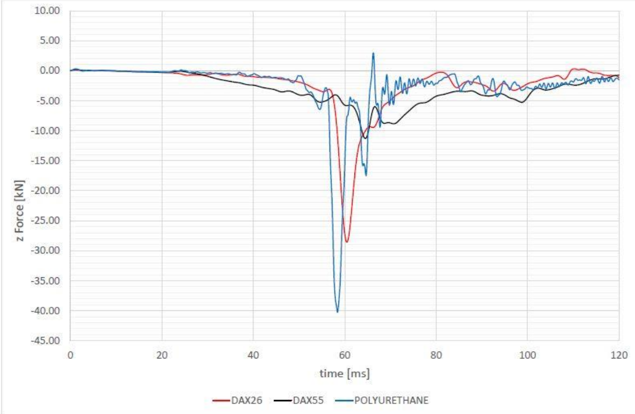

Figure 15 Lumbar forces acting on the occupant of rear seat

The observation of the red curves put in evidence that the lumbar force acting with a seat cushion made in DAX26 foam has a peak value of 1100 Kg for the occupant of forward seat and of about 3000 Kg for the occupant of rear seat. The limit imposed by regulations is 680 Kg and both the values are above it. The black curves, representative of the case of seat cushions made in DAX55 foam, show a peak force of 950 Kg for forward occupant and 1150 Kg for rear one. The blue curves, measured using a seat cushion of a generic Polyurethane foam, indicate a peak force of 710 Kg for forward occupant and 4000 Kg for rear one. It is so evident that in none of the situations the requirements have been satisfied.

TEST 2 Results In the case of Test 2, representative of a predominantly longitudinal impact, occupants are subjected to high loads acting primarily on the chest area, due to the interaction with the shoulder harnesses, and also to the risk of violent head strikes. To increase comfort and to improve the back protection, two backrest have been added to the model, made with the same foam of the seat cushions, DAX26.

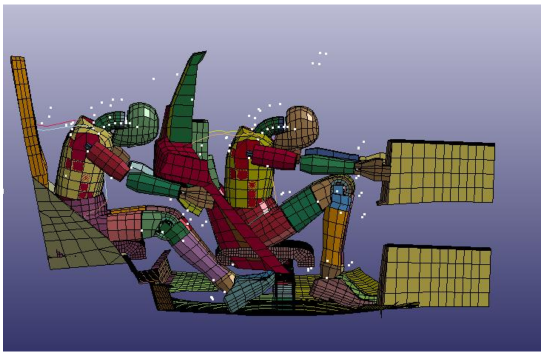

Figure 16 Detail of forward impact

The attention has been focused on measuring, besides the lumbar forces similarly to Test 1, the values of the loads acting on the shoulder harnesses that restraint the occupants, and on the verification of the occurrence of head impacts. For this purpose, by using the postprocessor LS-PREPOST have been observed: from output file "SBTOUT" the time evolution of the force applied to passengers' shoulder harnesses, and through the file "NODOUT", the values of the HIC parameter. Belt and lumbar forces can be read on the curves below.

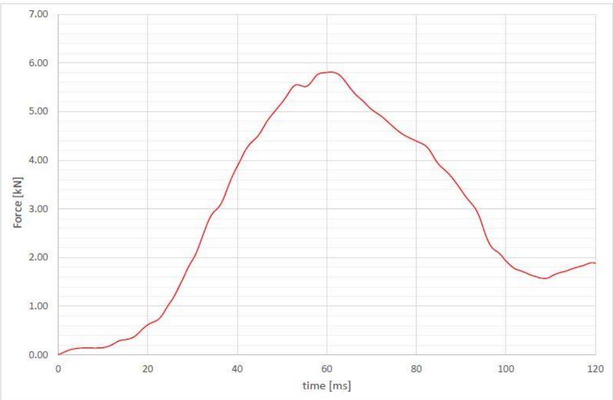

Figure 17 Force values on shoulder harnesses of forward seat

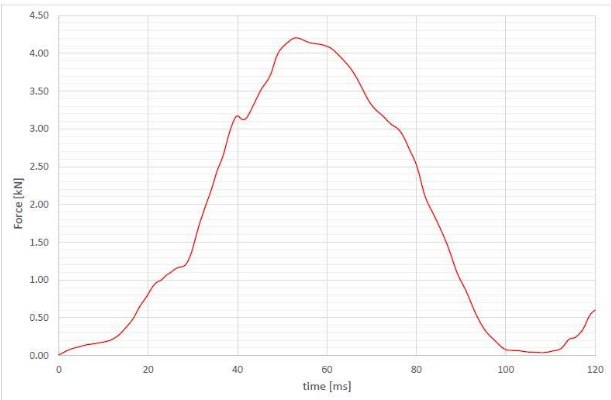

Figure 18 Force value on shoulder harnesses of rear seat

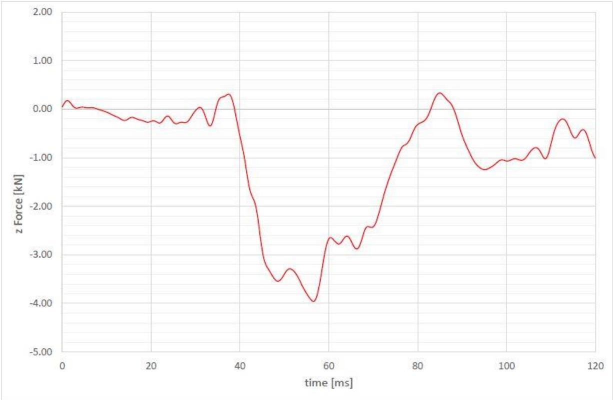

Figure 19 Lumbar force acting on forward occupant

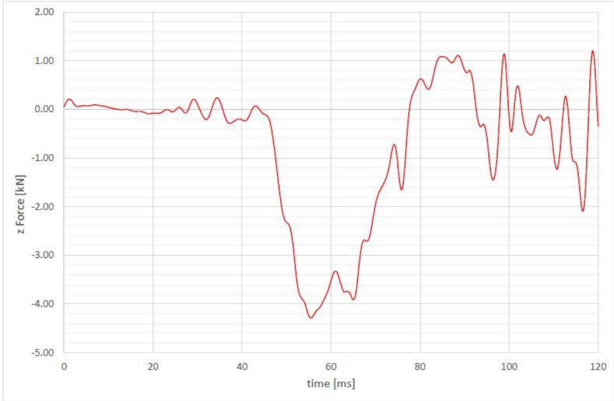

Figure 20 Lumbar force acting on rear occupant

All the force values measured in this analysis, meet the requirements. In fact, as previously seen, the regulations impose a maximum force measured on the belts of 794 Kg in case of individual shoulder harness strap, and 907 Kg for two straps. The maximum lumbar force must remain under 680 Kg. From the preceding curves, it is possible to observe that the peak forces acting on the forward occupant are about 580 Kg for belts and about 400 Kg for lumbar, while for the rear occupant are about 420 Kg for belts and 440 Kg for lumbar.

The HIC values, shown in Figure 21, have been calculated from the time histories of the accelerations measured in a node positioned in the middle of the head of each dummy, applying the relationship below.

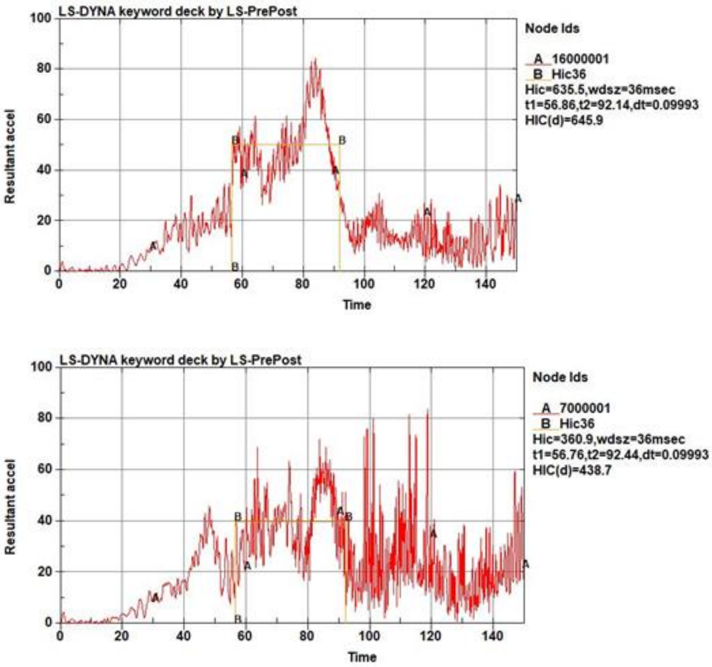

Figure 21 Acceleration profiles for HIC calculation for forward (up) and rear (down) occupants

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} \right\}_{max}$$

t_1 is the initial integration time, expressed in seconds
t_2 is the final integration time, expressed in seconds
$(t_2 - t_1)$ is the time duration of the major head impact, expressed in seconds
$a(t)$ is the resultant deceleration at the center of gravity of the head, expressed as a multiple of 'g'

The HIC value for forward occupant is 645, that for rear occupant 438, both below the limit of 1000.

V. Conclusions

The observation of the results put in evidence that the aircraft configuration does not provide adequate levels of human protection, so to demonstrate compliance with the regulations. In particular, the "worst case" has revealed to be vertical impact that shows lumbar force levels far above the fixed limits, while in the case of forward impacts all the requirements have been satisfied. The lone cushion, specifically for rear seat occupant, has not proved to be sufficient to ensure the necessary energy absorption. Moreover, the high difference between the forces applied to the lumbar column of the two passengers, has proved the influence of the seating position on injury dynamics. From what emerged, the next possible design steps could be further studies on the seat cushions foam, in particular looking for materials characterized, in their stress-strain relation, by an increase of maximum stiffness and a decrease of the densification strain. Future works will be oriented to the development of a new cushion concept suitable for this kind of aircrafts, realized as a "floating device", with a soft layer of open-cell rate dependent foam, above a semi-rigid surface of closed cell foam. The soft layer, adapting its shape to the bottom of the occupant, could provide comfort and offer a larger contact surface, so to prevent load concentration. The stronger crushable layer could ensure a solid sustaining structure and high energy absorption performances in case of a crash.

Acknowledgments

This work has been developed during my master degree thesis internship at the Department of Industrial Engineering of the University of Naples Federico II. There, I had the opportunity to appreciate the professionalism, the competence and helpfulness of Professor Francesco Marulo and Professor Michele Guida, and the precious cooperation of Eng. Tiziano Polito and Eng. Claudio Casale.

References

[1]T.R. Hurley, J.M. Vanderburg, *Small Airplane Crashworthiness Design Guide*, Simula, Inc., Phoenix, Arizona, April 2002

[2]*Certification Specifications for Normal, Utility, Aerobatic and Commuter Category Aeroplanes CS-23,* European Aviation Safety Agency, November 2003

[3]*Certification Specifications for Normal-Category Aeroplanes CS-23, Amendment 5,* European Aviation Safety Agency, March 2017

[4]*Advisory Circular No: 23.562-1, Dynamic testing of Part 23 Airplane seat/restraint systems and occupant protection*, U.S. Department of Transportation, Federal Aviation Administration, Washington, DC, June 1989

[5]*LS-DYNA Keyword User's Manual – Volume I,* Livermore Software Technology Corporation, August 2016

[6]*Advisory Circular No: 20-146, Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27 and 29 Airplanes and Rotorcraft,* U.S. Department of Transportation, Federal Aviation Administration, Washington, DC, May 2003

[7]*LS-DYNA Theory Manual,* Livermore Software Technology Corporation, March 2008

[8]*LS-DYNA Keyword User's Manual – Volume II Material Models,* Livermore Software Technology Corporation, April 2017

[9]M. Costa, L. Enrietti, E. Pasero, *Application of data driven techniques to the prediction of seat comfort performance,* Lear Corporation, Politecnico di Torino

[10]B. Croop, H. Lobo, *Selecting Material Models for the Simulation of Foams in LS-DYNA, 7th European LS-DYNA Conference,* DYNAmore GmbH, 2009

[11]P. Bhonge, *A Methodology for Aircraft Seat Certification by Dynamic Finite Element Analysis,* Department of Mechanical Engineering, Wichita State University, December 2008

[12]M. Pirozzi, *Caratterizzazione Metodologica FEM per la valutazione al Crash delle autovetture, Dipartimento di progettazione e Gestione industraile,* Università Federico II di Napoli, 2005