Research Activity at Politecnico di Milano Crash Test Laboratory

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Abstract

In the last year Politecnico di Milano has moved its crash test laboratory in a new site. This new location has allowed to develop new series of facilities and new research projects.

This paper reports the description of some activities and the corresponding new available facilities. The research projects are developed using experimental and numerical tools and particular attention is devoted to the integration between the two methods.

- Impacts against water surface.
  This research is devoted to the study of the interaction between structures and fluids during an impact. The numerical activity is developed using several finite element codes (Ls-Dyna, Esi/Pamcrash, Msc/Dytran), able to describe the continuum using both a Lagrangian approach and an Eulerian/Lagrangian approach. The experimental activity is now devoted, on one side, to obtain accurate pressure fields on rigid bodies during the impact and, on the other side, to study the behavior of real aeronautical structures in such condition. The water impacts are obtained using a new drop tower able to reach a maximum speed of 20 *m/s* with a mass of 1500 *kg* and a maximum specimen size of 4x4 *m*. The tower is equipped with a pool, having diameter equal to 8 *m* and depth equal to 0.8 *m*.
- Safety on cabin occupants.
  This research is devoted to the study of the interaction between aircraft occupants and surrounding structures during an impact. The investigated research fields vary from the study of anti-crash seats to the study of the influence of deceleration pulse shape on occupant movement and risk indexes. The numerical activity is conducted mainly using multi-body codes (Vedyac and Madymo), even if some new investigations are developed using also finite element codes. The experimental activity uses a horizontal sled, that presents a maximum length equal to 100 *m*, a maximum mass equal to 2.5 *ton* and a maximum velocity equal to 20 *m/s*. The same sled can be easily modified to perform standard crash tests and energy absorbing tests on road vehicles and safety barriers.
- Drop tests.
  This research is focused on the study of materials and sub-components during energy absorbing phenomena and is developed through experimental tests on composite and aluminum alloy specimens. The tests are carried out using a standard vertical drop test machine, that presents a maximum height of 6 *m* with a maximum mass equal to 1000 *kg*.

This paper has been prepared in order to introduce the new facilities of Politecnico di Milano crash test laboratory, reported in Figure 1, to the international scientific community and to present the new research activities in progress.

Fig 1. New crash test laboratory

IMPACTS AGAINST WATER SURFACE

The study of hydrodynamic impact between a body in motion and a free water surface finds applications, in aeronautical fields, in splashdown and ditching problems. The effect of this impact is often prominent in the design phase of the project and, therefore, the importance of studying the event with more accuracy than in the past is imperative.

Usually the study of the phenomenon is dealt with experiments, empirical laws, and, lately, with finite elements simulations. These simulations are performed by means of special codes that allow the fluid-structure coupling. These codes have their origin in Lagrangian finite element programs developed for crash analysis improved with the possibility of interfacing continues with Eulerian spatial description. Critical points in this kind of modeling are the fluid-structure interaction algorithms, constitutive modeling of the fluid and time efficiency of the computation.

The starting point of this work consisted in a deep bibliographic research that pointed out the actual results both in terms of experimental and numerical results [1-11]. Regarding the numerical approach of the phenomenon exhaustive results with a finite element modeling description have not been yet obtained. Concerning the experimental approach a big amount of work on impacts of rigid bodies is available. Therefore, the starting interest was concerned with the study of an impact of a rigid sphere on the water surface.

This problem is well known in aeronautical and naval fields. In aeronautical the problem is encountered during the splashdown and ditching, while in naval field the problem is deeply studied for the interaction between ships or offshore structures and waves. Anyhow the aim of these studies is to predict the loads transferred during the phenomenon to the structure. Two typical examples of these researches are the re-entering aerospace capsule faced by Alenia [10] and a probe [11] landing on the surface of Titan, the biggest Saturn satellite, impacting with an evaluated speed of 5 *m/s* on a possible impacting surface, a sea made of a liquid hydrocarbon.

Experimental drop tests

The experiments started with impacts conducted with a rigid instrumented sphere. These tests were performed with a rigid sphere with a diameter of 0.218 *m* and a speed of 11.8 *m/s* impacting vertically a water surface. The sphere was a bowling bowl with a mass of 3.76 *kg* and a density of 693 kg/m^3. It was machined on the surface to insert three piezoresistive accelerometers with a range of ± 100 *g*. These accelerometers were placed with the sensitivity axes forming an angle of 45° with the vertical and 120° between them in the horizontal plane.
The time history accelerations of the three accelerometers were compounded giving the rotation of the sphere, adopting the assumption of constant inclination of the sphere during the first 10 *ms* of the impact, and the resultant acceleration-time history.
In Fig. 2 the acceleration time histories of the two tests are reported. Both curves present the maximum peak at t =1.5 *ms* with a value of about 67 *g*. After this peak the acceleration decreases rapidly. A numerical activity was conducted using coupled finite element codes. The results of this activity are reported in Fig 3 with a comparison between numerical and experimental results.

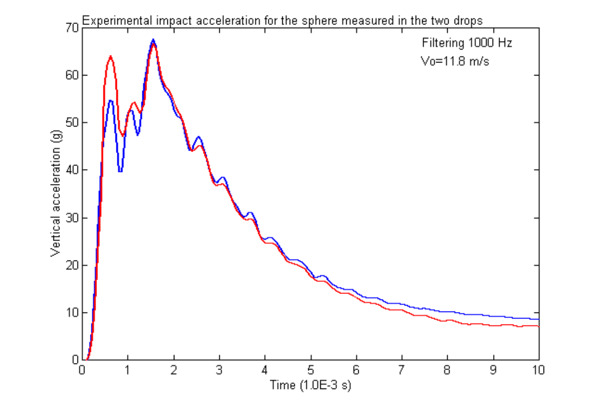


Fig 2. Rigid sphere acceleration-time history

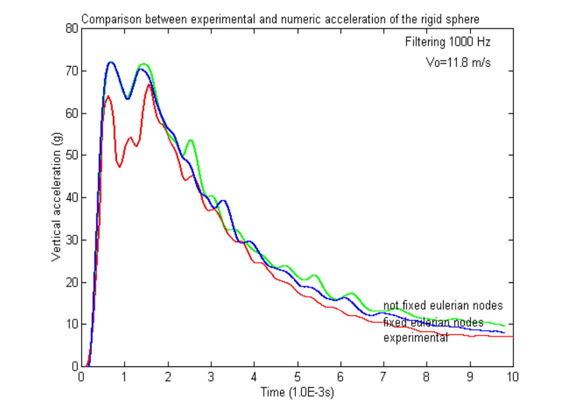


Fig 3. Numerical-experimental comparison

After these tests with a rigid sphere, impacts were conducted with a deformable body, build to represent a real stiffened aeronautical structure. In Fig. 4 and 5, two photographs of these tests are reported. This activity was conducted using also numerical finite element tools to better investigate the coupling between the structure and the fluid (Fig. 6-7).

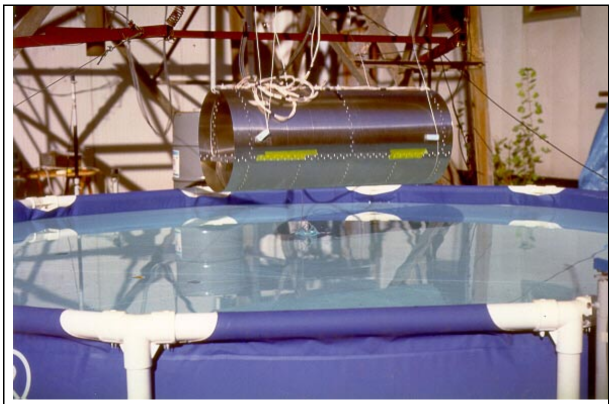
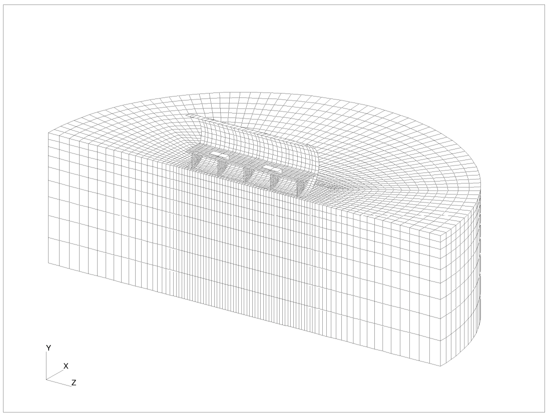


Fig 4. Deformable body impact

Fig 5 Deformable body impact



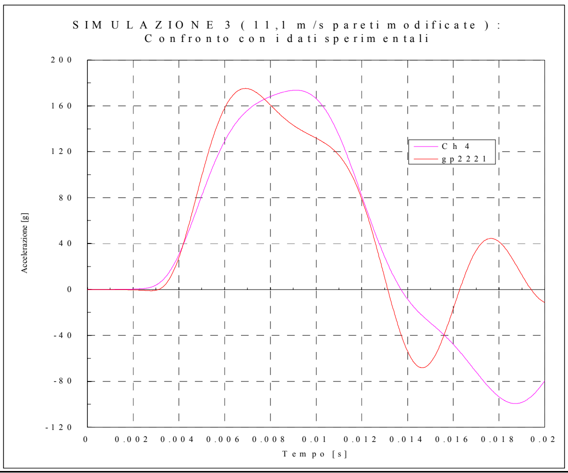
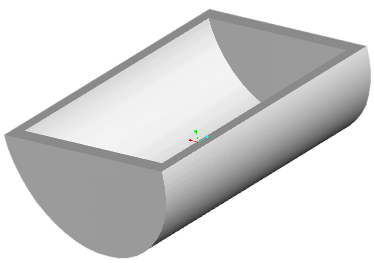


Fig 6. Deformable structure

Fig 7. Experimental and numerical result

The above described activities showed the need of more detailed results on simple structures. Detailed tests are now under investigation using simple rigid structures covered with pressure transducers to obtain experimental pressure contours. This experimental work is supported by the European Community inside the “CAST” project.

The shapes chosen for the tests are reported in Fig. 8 and 9.



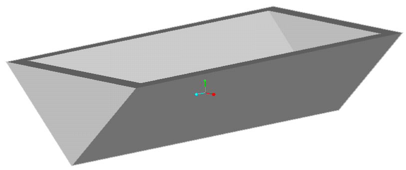


Fig 8. Cylindrical specimen

Fig 9. Pyramidal specimen

Using Ls-Dyna finite element simulation, the pressure transducer range as well as their location on the structures have been chosen. To perform these tests a new drop test machine has been build in the new laboratory (Fig 10). This tower is able to lift structures with a maximum mass of 1500 *kg* at 20 *m* above the water surface. Four cables will be used to guide the specimen during the free fall. In the lower part of the machine is located a pool with a diameter of 8 *m* and a depth of 0.8 *m*. Just above the surface of the water there is a control room where high speed cameras will be placed to have a good point of view. The location of the control room has been chosen to allow also underwater high speed camera films.

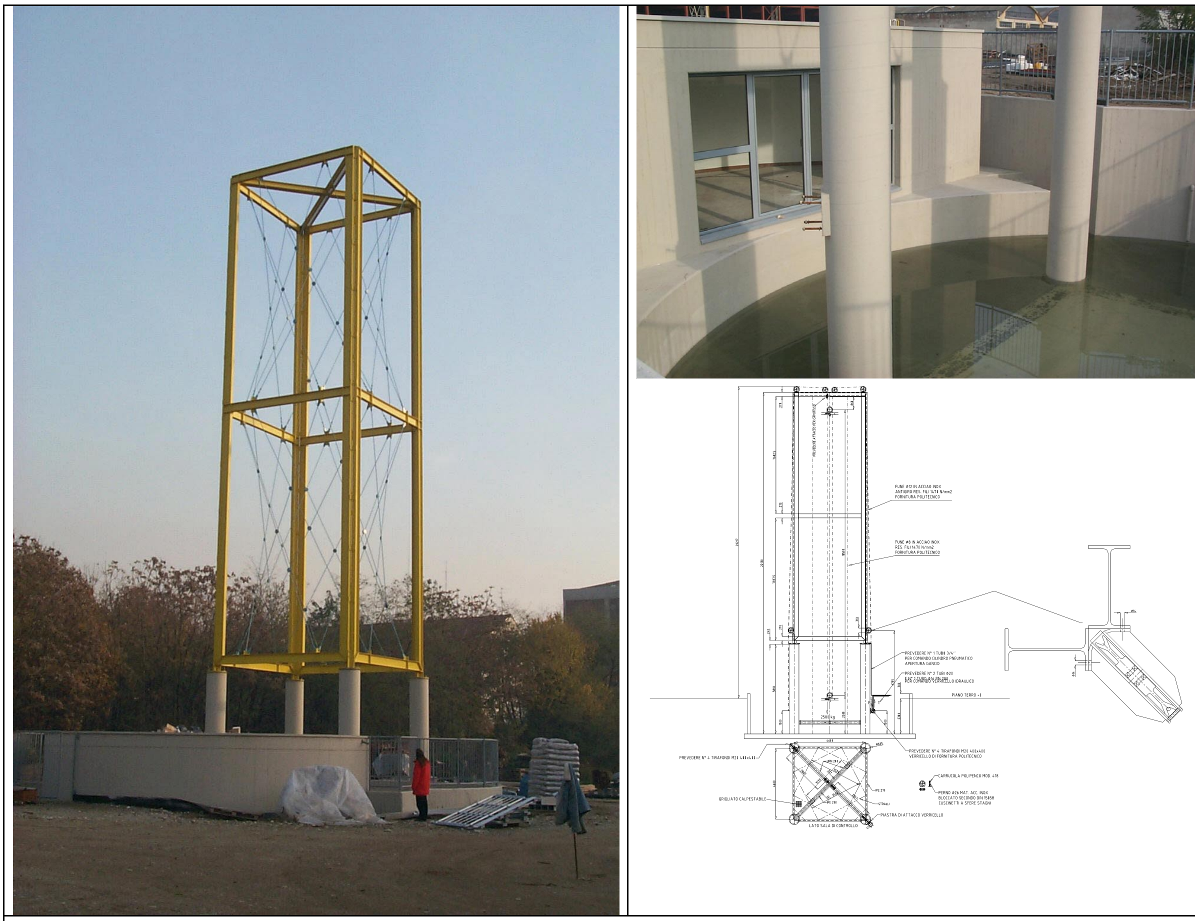


Fig 10. Drop test machine, control room and pool, tower drawing

SAFETY ON CABIN OCCUPANTS

This is a study on the characteristics and the limits of the current aircraft seat crash test homologation standards. Complying with them, a seat with an anthropomorphic test dummy must successfully complete dynamic tests in the directions, velocities, impact accelerations and corresponding rise time prescribed by FAR-25.562. Information and guidance regarding acceptable means of compliance with PART 25 of FAR, as well as graphical evaluation to compare different test deceleration curves are provided in AC 25.562-1A. However, it was noticed that different pulse shapes, although complying with the graphical procedure mentioned, lead to different loads on the dummy, allowing test facilities to obtain disagreeing results for the homologation of a seat. Focusing attention on the so-called “down” test, it was

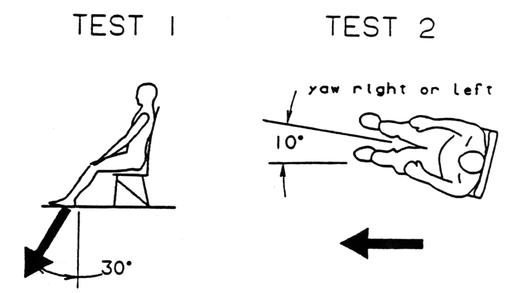


Fig 11. Down and forward crash test

intended to numerically analyze, with the aid of experimentally validated seat-occupant models, the consequences of using an erroneous test pulse shape and thus propose the use of an alternative equivalence criteria.

Certification standard

Nowadays aircraft seats must comply with two different dynamic homologation tests. One is the so-called "forward" test, in which the acceleration is only in the seat floor plane; the other is the so-called "down" test, in which the acceleration is mainly in the vertical direction (Fig. 11).
Risk of injury is evaluated by measuring the HIC parameter (1000 *s* maximum), femur loads (10000 *N* maximum) and upper torso restraint loads in the forward test and the compression load in the lumbar spine in the down test (6670 *N* maximum). Both tests are characterized by a triangular acceleration pulse shape (Fig. 12) [12].
The filtered acceleration pulse is acceptable if the plotted data are equal or greater than the ideal impact pulse. However, this can lead to using a test pulse significantly higher than the ideal pulse unless the test facility has precise control in generating the test pulse. To avoid this problem, an alternate graphic technique may be used to evaluate test impact pulse shapes, which are not precise isosceles triangles.
This graphic technique (which in the meantime has been modified by FAA) uses a step by step procedure on the filtered acceleration test pulse. If the pulse shape satisfies this graphical procedure and the injury criteria are within their limits, then the seat is considered certified.

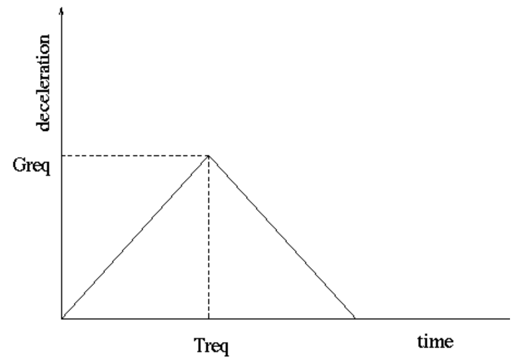


Fig 12. Ideal pulse shape

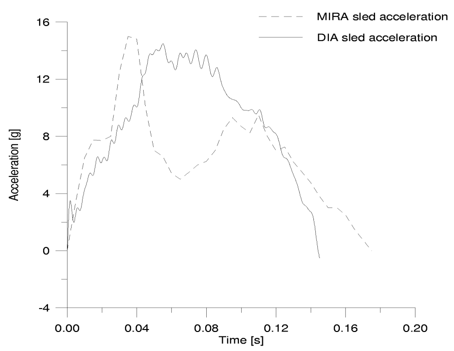


Fig 13. Different experimental acceleration pulse shapes

While the above mentioned procedure should be used to asses "minor" pulse shapes deviations from the ideal one, it was noticed that different test facilities used it to validate pulse shapes that are very different from the ideal one (Fig. 12). It was also noticed that different pulse shapes, although complying with the graphical procedure, lead to different loads on the dummy, allowing test facilities to obtain disagreeing results for the homologation of a seat. For these reasons and after a test evaluation of the effects of erroneous pulse shapes [14], the graphical procedure, described above and here taken into consideration, has recently been modified by FAA with a memorandum [15].
In order to point out, with the use of numerical simulations, the effects of different pulse shapes, deceleration curves that maximize and minimize the compression of the lumbar spine

were found: the first not satisfying and the second satisfying the above-mentioned criteria of "equivalence".

The model

Investigation was carried out with the extensive use of a multi-body program named VeDyAC for the simulation of the impact dynamic of the seat-occupant system. The seat, manufactured by an Italian society, is a double seat row, with four legs that must be connected to the floor tracks of the airplane and are asymmetrical if seen in a frontal view. The main seat structure is made of aluminum alloy. The occupants are 50th percentile HYBRID II anthropomorphic dummies (Fig. 14).

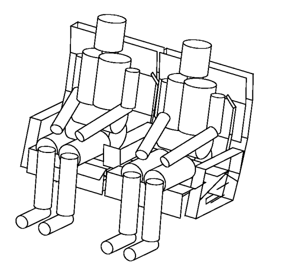


Fig 14. VeDyAC model of the seat-occupant system

The model of the ATD is made of 13 rigid bodies, each having the inertia properties of the corresponding part of a 50th percentile HYBRID II dummy. The dummy model is compliant with dummy's calibration standards [16]. The mechanical properties of the cushion, which play a main role in the down test, were instead obtained by means of a drop tower. The model was developed in a previous work [17] and experimentally validated using the crash test facilities of the Aerospace Engineering Department of Politecnico di Milano (Fig 15).

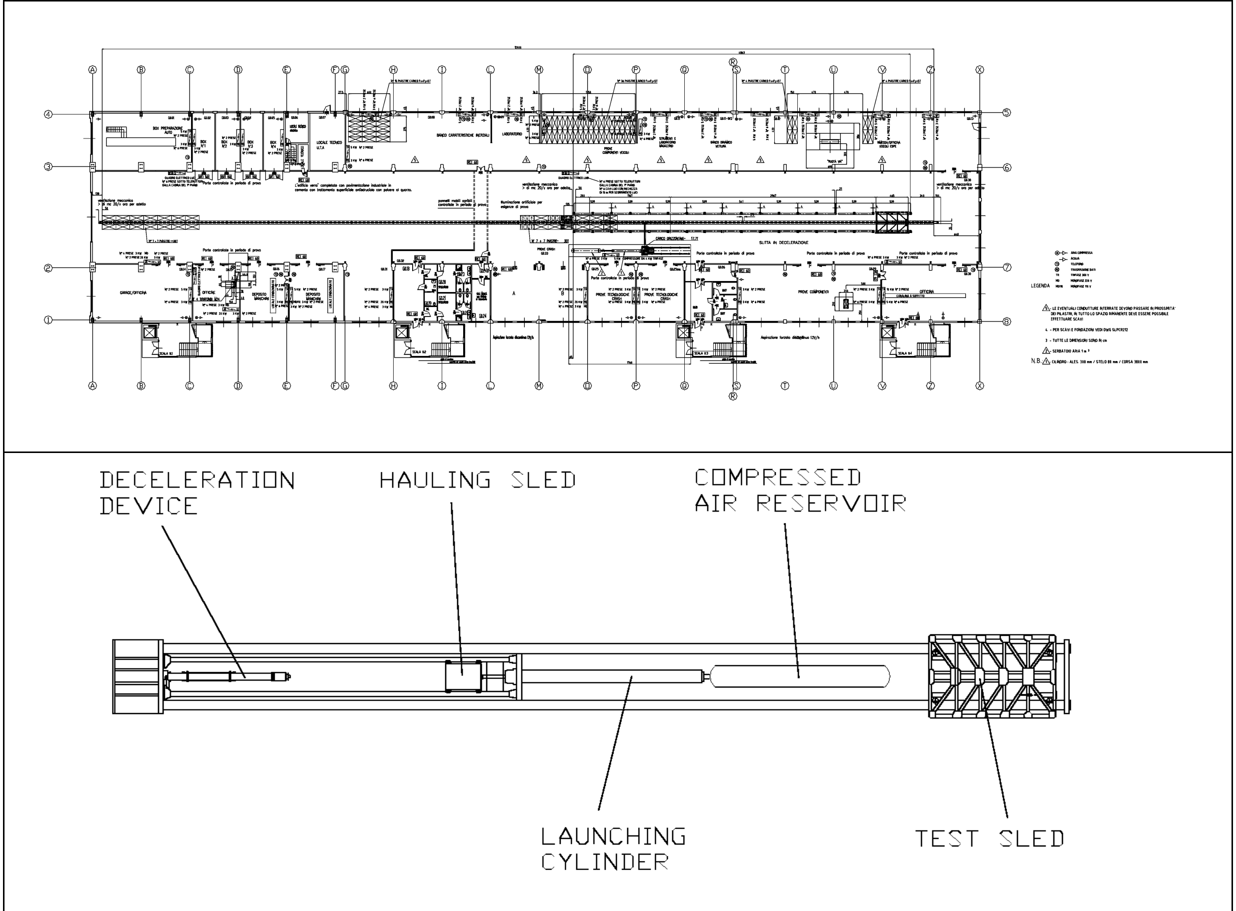


Fig 15. Crash test sled facility (new and old version)

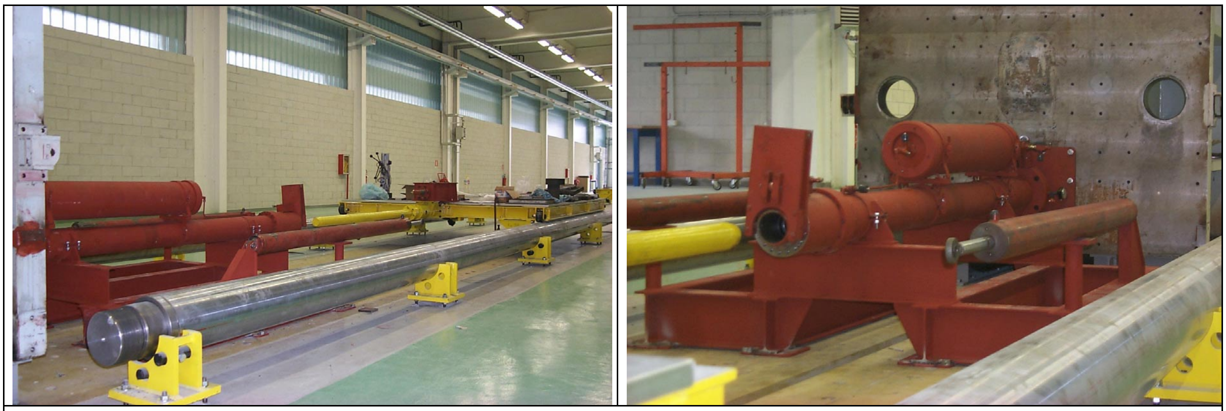


Fig 16. Hydro-pneumatic brake

The seats are mounted on the deceleration sled running on two horizontal rails. The initial velocity is reached by means of a compressed air piston that pushes the hauling sled to which the test sled is connected by means of a series of wire rope pulleys. The run distance is relatively long (19 *m* in the old version, 45 *m* in the new version), so that the acceleration is slow enough to prevent the dummies to move from their correct seated position. The sled is able to sustain a maximum load of 2500 *kg*. After a few meters of free run, the sled is decelerated by means of a pre-calibrated hydro-pneumatic brake (Fig. 16) that provides the requested pulse. During the impact phase data acquisition systems and high speed cameras are running.
The deceleration pulses, used to validate the seat-occupant model, correspond to FAR requirements, even if it was not important for the validation in itself.
As shown in Fig. 17, good agreement is obtained between numerical and experimental results, especially for the lumbar load.

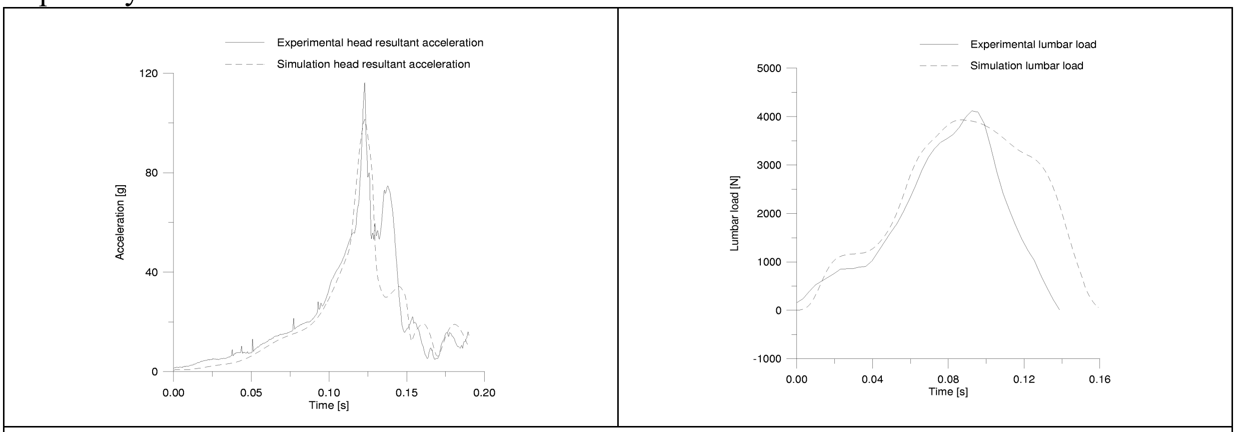


Fig 17. Experimental-numerical comparison

The optimization problem
As mentioned before, the intention is to understand how the shape of the deceleration pulse can influence the results of a homologation test, still satisfying the equivalence criteria imposed by the standards. It must be stressed that the subject of the investigation is not the adequacy of the ideal triangular pulse shape, but the equivalence criteria between the ideal and a real homologation test curve. With the experimental validation of the seat-occupant model it

was possible to analyze the response of the dynamic system subjected to a generic deceleration history. Allowing arbitrary variation of the deceleration pulse shape, it was possible to minimize the dummy lumbar load still satisfying the standards equivalence criteria. On the other side, it was also possible to maximize the lumbar load without satisfying the standards. Clearly, the last is done imposing criteria which are exactly the opposite of those prescribed by the standards.
The optimization was performed using a genetic algorithm, which need only objective function evaluation and are quite insensitive to the hill-conditioning of the response surface and the presence of local minima [18]. For these reasons they seemed to be the best choice for the analysis of this type of problems.

Results
The results are quite disappointing in that one would expect to find very similar values for the minimum and maximum compression load in the lumbar spine, while it was possible to find a difference of more than one thousand Newton between the maximum and the minimum lumbar load (Fig. 18)
To find a minimum in the lumbar load, the easiest way is to maintain it constant over the entire duration of the pulse. The corresponding deceleration curve reflects this kind of search, showing an initial peak which determines the initial lumbar load peak. Being this acceleration peak at the very beginning of the entire pulse, and having to satisfy the change in velocity requirements of the standards, the acceleration curve does not go to zero and changes in such a way to produce a practically constant value in the lumbar spine compression. On the other side, the maximum lumbar load is achieved with an abrupt deceleration at the end of the pulse, the initial peak being prevented by the constraints imposing the violation of the equivalence criteria, and especially of the minimum rise time T_{req}.

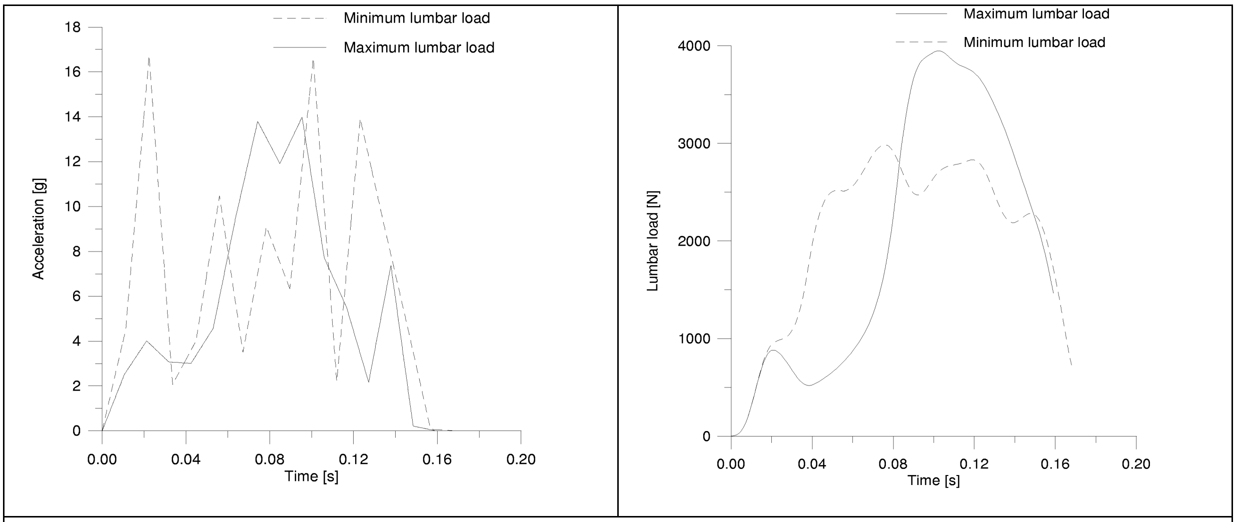


Fig 18. Unfiltered deceleration curves and corresponding lumbar loads

It is quite impressive to notice that the "minimum" deceleration curve is similar to those used in some crash test laboratories (Fig. 13), while the "maximum" deceleration curve led to an almost identical lumbar load to that of the ideal triangular pulse (Fig. 12).
The results of these analyses show that not only the initial peak, but the entire deceleration history is critical in evaluating the risk of injury in the vertical impact test. Indeed, without a

reduction of the deceleration after the initial peak, and a subsequent proper shape, it would not be possible to keep the lumbar load at a low, constant level. Imposing the magnitude of the acquired pulse to be at most 2 *g*'s less than the ideal, during the entire time interval, a deceleration history leading to a constant lumbar load could not be achieved, and the difference between the maximum and the minimum lumbar load becomes nearly negligible.

DROP TESTS

An extensive study was performed, aimed at first to characterize different composite material systems (reinforcement, matrix, stacking sequence and degree of hybridization) using simple cylindrical specimens, then to assess and compare components and assemblies design solutions, finally to evaluate numerical tools for crash simulations.

The experimental activity was performed on 200 tubular specimens, 200 *mm* high, 80 and 160 *mm* in diameter, with diameter to thickness ratio ranging from 24 to 175. The tubular specimens were adopted due to the easy detectability of energy absorbing mechanisms. Besides, the results can be compared to the ones obtained by other authors and the production of composite tubes is relatively easy and cheap by means of wrapping or filament winding techniques. The specimens were produced using different types of epoxy pre-pregs: carbon unidirectional and fabric, aramidic unidirectional and fabric, and hybrid carbon-aramidic, each characterized by different orientations, stacking sequences and foam core presence. The core volume of the foamed specimens was reduced to avoid anomalous laminate failure due to the foam incompressibility threshold reached during dynamic tests. The specimens upper edge of cylinders was 60° beveled to decrease the initial load peak. A drop weight test machine was used; accelerations and displacements were sampled at 10 *kHz* and low-pass filtered at 1 *kHz*. Three tests were performed for each type of specimen and for each load condition: quasi-static, 6, 8 and 10 *m/s* impact velocity, at 3.5 *kJ* constant energy content. Compared to aluminum alloy specimens, the carbon tubes showed a load sustained more uniformly and, on the contrary, a higher average dynamic strength. From the other side, they did not maintained a satisfactory post-crash structural integrity. A photo of two crushed composite tubes and a crushed aluminum alloy tube is reported in Fig 19.

Fig 19. Tested cylindrical specimens

Experimental tests were then performed to compare components and assemblies design solutions and to evaluate numerical tools for crash simulations. An extent investigation was developed for the design of an energy absorbing aluminum helicopter subfloor. To identify the detailed design and the structural concepts for the most efficient mechanism of energy absorption, typical subfloor components were tested. Design aspects focus in more detail on the subfloor structural intersections, because, under vertical crash loads, they can create high deceleration peak loads at the cabin floor level and cause dangerous inputs to the seat/occupant system.

Fig 20 shows a photo of riveted structural intersections before and after testing [19-20], while Fig 21 reports a typical diagram obtained performing drop tests from a height of 2.8 *m*, giving an impact velocity of 7.4 *m/s*. Up to first failure, the specimen stiffness and strength are controlled, while the crushing of the component happens by plastic deformation and controlled fractures of the metal sheets. In the tests performed on the structural intersections, the peak force is about 52 *kN*, while the average crush force level ranges from 25.5 to 28 *kN*. The specific energy is about 6.5 *kJ/kg*.

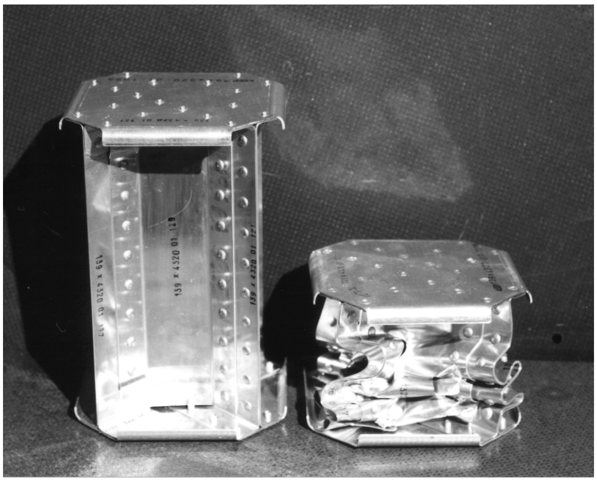


Fig 20. Helicopter subfloor intersections before and after test

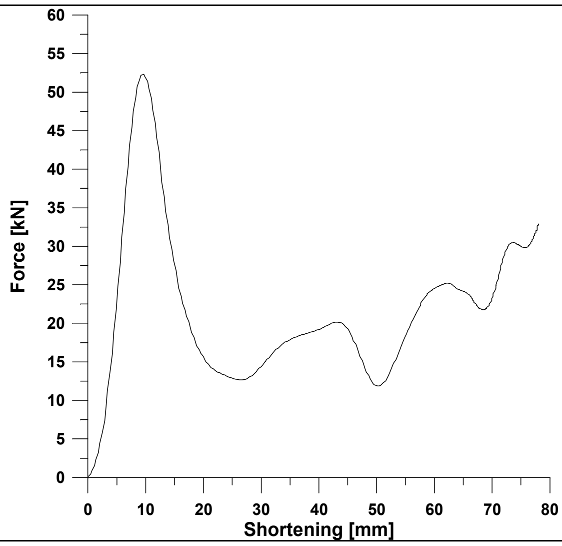


Fig 21. Typical force/shortening diagram

Fig 22. Landing gear test

Besides these activities on materials and structure sub-components, the vertical drop test machine was also used to test landing gears. A helicopter main landing gear, mounted on a special sled designed to be easily modified adding mass between different tests, is reported in Fig 22.

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