CRASHWORTHINESS OF SEAT AND RESTRAINT SYSTEMS IN CIVIL AIRPLANES

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ABSTRACT

Both FAR and JAR regulations require crash performance and occupant protection for seat and restraint systems, that must be ascertained in dynamic tests.
The main difficulties in design and testing come from lack of experience in such a new field and from the interpretation of the new regulation by the authority, particularly where rational choices are required, as for example when a critical case must be selected among a large amount of possibilities.

The paper reports the experience of the laboratory of Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, on several aircraft seats, that have been analysed, modified and tested to qualification thanks to an extended use of hybrid simulation, i.e. a computer simulation relying on laboratory data for component behaviour.
Optimum modification has been searched by simulation, then verified at component level by laboratory tests, and finally qualified by a small number of full scale dynamic tests.
In some cases the extended use of simulation allowed to minimise the cost and weight of the modification required to fulfil the requirements.
In another case the simulation led to the only possible answer to the tough demand of limiting the compression of the spine of the two occupants of a small airplane, the two sitting 4.5" above the main wing spar.

In the future the design of new seats will take advantage from all this experience, i.e. from the experience in the use of hybrid simulation and in the application of new structural concepts for energy absorption and impact attenuation.

INTRODUCTION

The increase of safety of an aircraft is obtained principally by reducing accident probability, i.e. developing active safety concepts. On the other hand it is difficult to reduce that probability beyond the present limits, most of all due to the human factor.
Therefore occupant safety must be increased by developing crashworthiness criteria, that is by designing the aircraft in such a way that, if accident occurs, occupant risks are minimised.
Partially survivable accidents are considered when studying aircraft crashworthiness, in particular emergency landings.
During this kind of landings the main risk to be reduced is the post-crash fire, due to the leakage of the fuel system, and the collapse of the cockpit with consequent elimination of the liveable space around the occupants.
Other possible causes of injury are high accelerations on some human body sections and the contact between some vital parts of the body and the surrounding surfaces. In both these cases the seat and restraint system play a basic role for injury prevention. In fact the international aviation rules require also a crash certification for the aircraft consisting in dynamic tests to be performed on the seat-cockpit system.

In the tests instrumented anthropometric dummies are employed to reproduce realistic dynamic loads in the seat and belts and to measure loads and accelerations in critic points of the human body.
Pass/fail criteria are essentially based on structural integrity of the seat and injury risk criteria based on data acquisition from the anthropometric test dummies (ATD).

THE EMERGENCY LANDING: PROBLEM DEFINITION

The emergency landing is the typical situation that an aircraft may experience after a flight malfunction or failure. In many cases this landing is strong enough to produce structure plastic deformation and high accelerations in the internal structure around the passengers.
The deformation may involve the floor and induce pre-tensions in the seat structure, before the main acceleration pulse occurs.
Normally the passengers are seated with their seat belts fastened, and therefore the impact accelerations have the following dynamic effects on the structures studied in this work:

- inertial forces on occupants and seats;
- belt tensions;
- seat structure tensions;
- seat-floor attachment loads;
- relative motion between the occupant and the surrounding surfaces with risk of contact and high local

accelerations and loads; typically the impact of the head against the front seat row in a civil transport aircraft or against the transparent in a light aircraft, and the impact of the upper leg with consequent risk of femur fracture;

- relative motion between the occupant and the seat during an impact with significant vertical component of acceleration that causes a dangerous compression of the lumbar spine.

The typical emergency landing condition implies both vertical and horizontal accelerations, with low lateral components. In the case of a civil transport airplane this may result in too large residual deformations of the seat rows and difficulty for passengers to move from the seat and escape from the aircraft at the end of the impact.

OCCUPANT RISKS

As stated before, the main cause of death in aircraft accidents is post-crash fire, which at present is reduced by including anti-misting additives in the fuel.
As far as the mechanical injuries are concerned, they change in severity and frequency according to their localisation on the human body. When performing seat crash tests, the use of instrumented anthropometric dummies provides the data necessary to evaluate injury risks.

The arms and legs are the most frequently injured segments of the human body, because they are not restrained by safety belts and then flail during the impact. Normally these kinds of injuries are not directly fatal, if no large haemorrhages come, but leg injuries, such as femur fracture, may result in impossibility or great difficulty for the passenger to leave the aircraft after the impact, thus being exposed to the risk of post-crash fire.
The typical femur fracture is due to compressive loads. For a standard male, 1000 kg can be considered the fracture load.

The head contact against surrounding objects is less frequent than the leg and arm contact, but is more dangerous. Many studies have been done about brain trauma, correlating it with acceleration time history. The most accepted index at present is the Head Injury Criterion (HIC), which is calculated according to the following equation:

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

where:
a(t) is the head resultant acceleration expressed in g's;
t1 and t2 are the two instants during the head impact that maximise the above expression.

The HIC calculation can be easily performed by a computer program that scans all the acceleration-time history during head impact.
If time is expressed in seconds, the maximum safety value is considered to be HIC = 1000 s.

When the impact velocity has a significant vertical component, one of the main occupant risks is the compression fracture of the lumbar spine, due to the inertial load of the upper body segments. In most observed cases, this injury is not fatal but may cause leg paralysis thus preventing the injured passenger from escaping. Moreover it may cause permanent disability.
It is commonly assumed that the compressive load of 675 kg is the tolerable limit.

When the impact velocity has a significant longitudinal component, the occupant pelvis may rotate and slide under the lap belt if no inguinal belt is mounted. This motion, known as *submarining*, is dangerous first of all because it allows large displacement of the human body, with consequent risk of contacts principally of the legs, and then because it bends the lumbar spine, reducing dramatically its tolerance to compressive loads.

SEAT STRUCTURE REQUIREMENTS

After pointing out the main effects of a ground impact of an aircraft on the seat and restraint system and occupants, it is not difficult to define the main requirements of the seat structure:

- the seat must remain attached to the floor;
- the seat residual deformation must be relatively small, to make easier the airplane emergency evacuation process;
- the seat and restraint system must prevent submarining: this can be obtained by designing properly the seat pan or adding an inguinal strap to the belt system;
- in multiple seat row systems (transport airplanes) the back rest must have a surface softness that prevents brain trauma of the rear passengers during aircraft impacts with significant longitudinal velocity.

It is actually difficult to satisfy in the same time the first 2 points of the list. In fact to prevent the seat from breaking the attachments to the floor during impact acceleration, it is necessary to reduce the dynamic loads on the attachments, which can usually be achieved by allowing important plastic deformations of the seat structure.
Problems are solved in different ways, depending on the aircraft category. In the present work 2 different kinds of airplanes are considered, i.e. the new Airbus A340 Business Class Seat and the GENERALAVIA F22 "Pinguino" seat, the latter one being a new acrobatic category propeller airplane.

The 2 types of seats are completely different and the impact conditions required by international regulations are also different in the 2 cases.

At the beginning of this research, the two seats were not designed for crash certification and actually the first tests were completely unsuccessful.

INTERNATIONAL REGULATIONS

The guidelines used to perform seat and restraint system crash testing are SAE AS8049 e AC 25.562. These reports provide information about the requirements of test set up and procedure, data acquisition system, high speed camera films, impact conditions, acceleration pulse shape and pass/fail criteria.

Fig.1 shows the impact conditions for the 2 different kinds of aircraft seats reported as examples in the present work. The first one refers to a typical civil transport aircraft seat, the second one to a light airplane, with the seat frame integrated in the aircraft structure.

In both cases 2 kinds of test are required:

- Test 1 reproduces a load condition during a crash landing with main vertical component of velocity and small longitudinal component;
- Test 2 refers instead to a crash landing with main longitudinal component of velocity and small lateral component.

In all cases the acceleration must be close to a triang pulse, with a specified rise time, or acceleration gradient, and peak acceleration.

Apart from the numerical values of impact velocity, rise time and peak acceleration, the main differences between civil transport and acrobatic aircraft seat testing lies in the number of seats to be tested and the problem of the floor deformation.

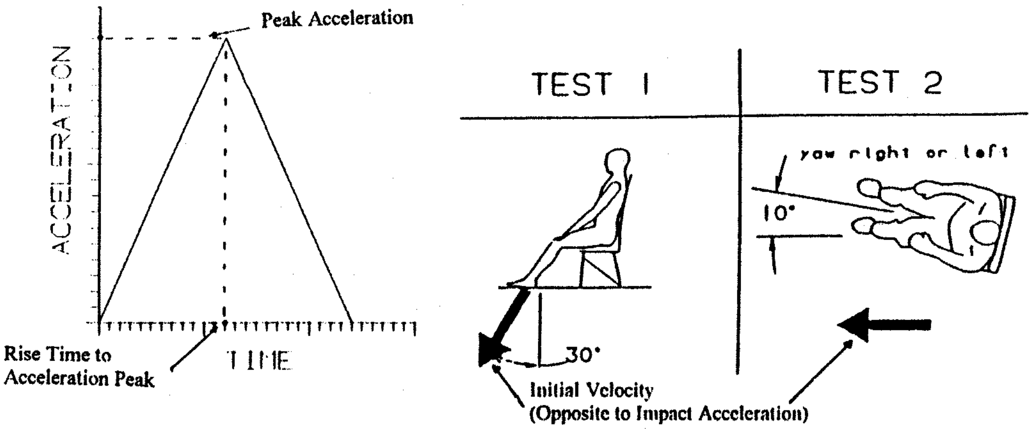
In the first case Test 2 must be performed with 2 seat rows to observe the head impact of the rear passengers against the front seats. Moreover the floor under the seat attachment must be deformed before the impact test: the floor must be rolled under one couple of seat legs and must be pitched under the other couple. Many combinations of floor deformations are possible (see fig.2):

- roll clockwise/anticlockwise left/right hand couple;
- pitch up/down right/left hand couple.

The seat rows also must be mounted in a ±10° yaw angle, which implies differences if the seat row is not symmetrical with respect to a longitudinal vertical plane.

All this brings to a combination of 16 possible configurations:

Among all these possibilities the worst configuration must be chosen and the seat must be tested in that configuration.



	TEST 1	TEST 2
TRANSPORT AIRPLANES		
MIN INITIAL VELOCITY [m/s]	10.67	13.41
MAX RISE TIME TO ACCELERATION PEAK [s]	0.08	0.09
MIN PEAK ACCELERATION [g]	14	16
ACROBATIC AIRPLANES		
MIN INITIAL VELOCITY [m/s]	9.46	12.81
MAX RISE TIME TO ACCELERATION PEAK [s]	0.05	0.05
MIN PEAK ACCELERATION [g]	19	26

fig.1

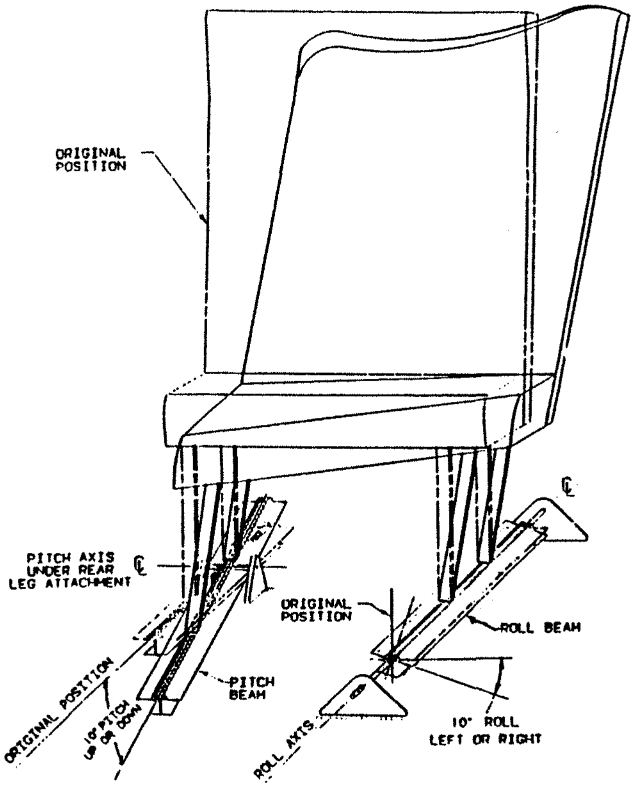


Fig.2

Such a problem does not come out in the seat testing of the acrobatic aircraft because it is a side-by-side seat airplane and the only possible contact of the occupant is against the surrounding cockpit or transparent. In this case the test item is in fact a complete fuselage section comprising the cockpit, with one seat mounted.

EXPERIMENTAL EQUIPMENT

The present section describes the crash facility used to perform the certification tests on the seats and the other one used for calibration tests on structural sub components of the seats.

The main crash test facility is reported in fig.3. It is called a *deceleration sled facility* because the test item, after reaching the requested velocity, is decelerated according to the normalised pulse shape.
The seats or fuselage are mounted on a sled running on 2 horizontal rails. The initial velocity is reached by means of a compressed air piston that pushes the sled for a relatively long distance (4 metres), so that the acceleration is low enough to prevent the dummies from moving from their correct seated position. The compressed air system is capable to accelerate a 2000 kg sled up to the velocity of 15 m/s.
After a short free run, the sled is decelerated by means of a pre-calibrated hydro-pneumatic brake, that provides the requested pulse.

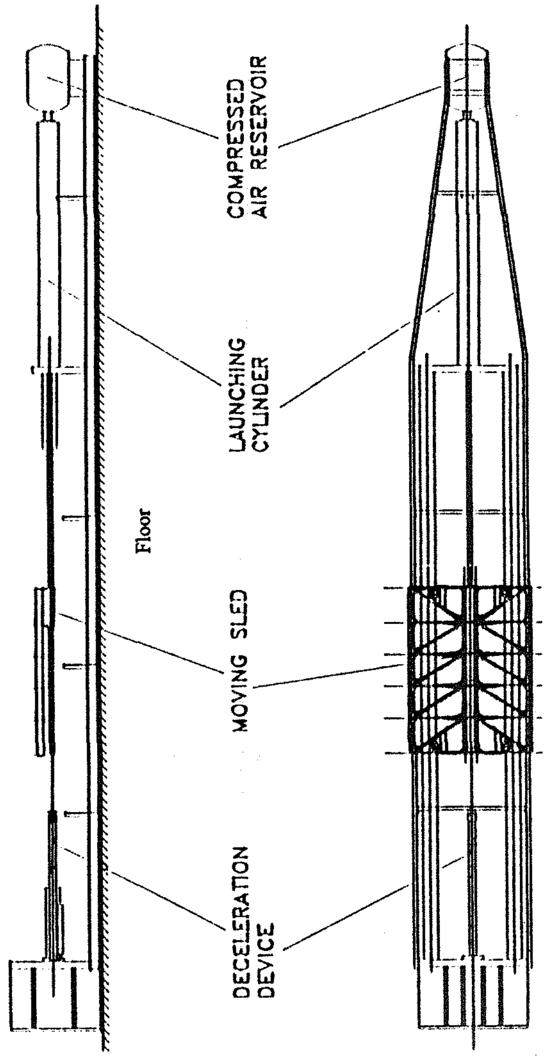


Fig.3

During the impact phase data acquisition systems and high speed cameras are running. The sampled data are:

- sled position;
- sled velocity at beginning of impact;
- sled acceleration;
- seat-floor attachment loads (in civil transport aircraft category);
- seat belt tensions;
- ATD head accelerations;
- ATD lumbar spine load;
- ATD femur load.

The sampling frequency is between 8000 and 10000 Hz and the signals are digitally filtered after the experiment, according to SAE J211.

The second crash test facility is reported in fig.4. It is a drop tower, capable of dropping a 300 kg sled with a final velocity of 10.5 m/s. This device only allows crash testing on small components, and has in fact been used to test and calibrate the seat pans and cushions, also providing mechanical data for the numerical model of the seat and dummy-seat interaction.

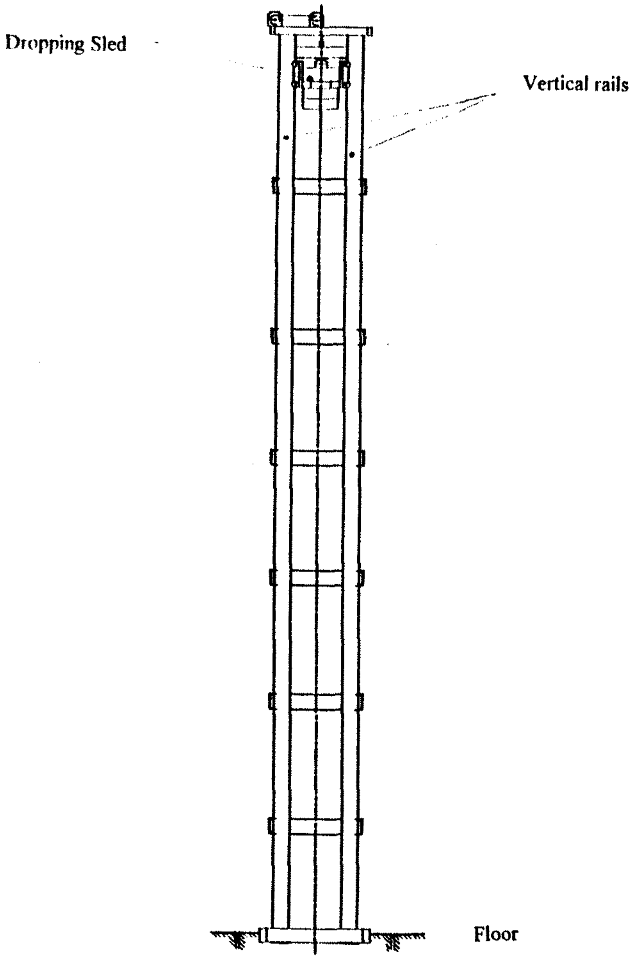


Fig.4

HYBRID SIMULATION OF THE EXPERIMENTAL TESTS

The crash test is formally required for certification and the numerical simulation cannot substitute it. In the present work the simulation of the experimental testing has been successfully used to improve and optimise the seat structure until certification.
Most of the simulations were performed with a multi-body code, named VEDYAC. In the simulation of F22 seat also the well known MADYMO code, by TNO, was used.

VEDYAC was developed in this Department with the co-operation and the financial support of the Dutch Institution SWOV (Institute for road safety research) since 1980. It is based on lumped parameter modelling. Being very flexible in use, it has been used very extensively for more than 10 years by SWOV and by this Department for many different purposes, from roadside barrier design to crash victim injury prediction. In this time both SWOV and this Department have acquired a good modelling experience and significant confidence in the results of carefully modelled simulations.
The main components of VEDYAC models are:

rigid bodies
nodes
deformable elements
contact surfaces

Rigid Bodies
Rigid bodies are defined in terms of inertial properties, i.e. mass, location of the center of gravity, moments and products of inertia. The dynamics of the system is obtained by integrating twice the acceleration (linear and angular) of the rigid bodies due to the effect of the reaction forces from deformable elements and from the contact forces.

Nodes
Nodes are connection points solid with the rigid bodies; they can be connected to deformable elements or to contact surfaces.

Deformable Elements
Deformable elements are massless structural components, generally elastic-plastic strain hardening. Deformable element types can be:

hinges
rods
beams

A hinge is a deformable point connection, having the possibility of angular reactions.
A rod is a one-dimensional element, connecting two nodes, capable only of axial forces. It may have play and any kind of asymmetry, as in the case of a rope or a belts (no compression).
A beam is a structural element, connecting two nodes, having two elastic-plastic bending hinges at its ends; it is also capable of axial and torsional deformation and reaction.

Contact Surfaces
Contact surfaces are used to find possible contacts and to simulate forces originating from contacts between different parts of the models. A contact surface can be:

flat surface
polyhedron
cylinder
sphere
surface of revolution

A polyhedron is an assembly of flat surfaces of limited extension. A cylinder is a part of a circular cylinder limited by two orthogonal sections.
In general a contact force has a component perpendicular to the contact itself, and a component tangent to the contact.
To compute the force of a contact of any surface with a flat surface or with a face of a polyhedron, first the interference of the surface with the flat face is computed. The normal force is then evaluated as the product of the interference area by a contact pressure;

such normal force is considered to be applied to the centroid of the interference area , perpendicular to the interference area. The contact pressure in general is a function of the penetration and of the penetration rate. Different contact pressure and pressure variation laws can simulate different hardness of the contact, from a very soft cushion to a very hard metal plate.

The tangent component is computed as a friction force, i.e. a force tangent to the interference area, applied to the centroid, equal to the normal force multiplied by a friction coefficient, parallel and opposite to the relative sliding of the two contacting surfaces. Such friction coefficient in general depends on the properties of both the contacting surfaces and may also depend on the relative sliding velocity.

The forces originated from the contact between cylinders or with other surfaces of revolution has a normal component depending on the penetration and on the penetration rate, plus a tangent friction component.

Fig.5 reports a schematic representation of the main VEDYAC elements.

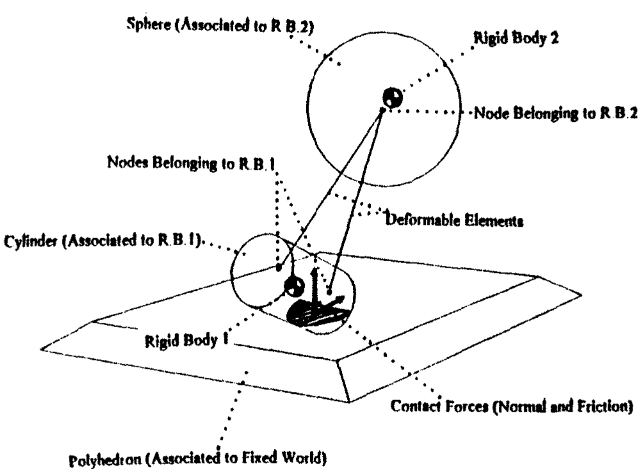


Fig.5

VEDYAC belongs to that category of codes, like KRASH, also referred to as *hybrid codes*, because the input data, such as deformable elements stiffness and plastic limits or contact surfaces characteristics, may be obtained mainly by experimental testing on sub components of the entire structure, or even by manual computations if the sub component is simple, or by finite element methods.

The simulation was used in the present work as support to the experimental testing, i.e. after validating the model all solutions and modifications were investigated by numerical simulation and then tested experimentally. This procedure brought to the final result, that is to the seat and restraint system crash certification, with a small number of crash tests, therefore reducing the time and cost of the seat structure optimisation.

CASE 1: AIRBUS A340 BUSINESS CLASS SEAT

The seat, manufactured by the italian company AVIOINTERIORS, is a double seat row, with four legs that must be connected to the floor tracks of the airplane and that are asymmetrical if seen in a frontal view (see fig.6).

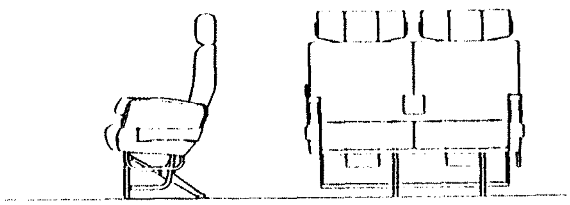


Fig.6

The main seat structure, made of an aluminium alloy, is shown in fig.7.

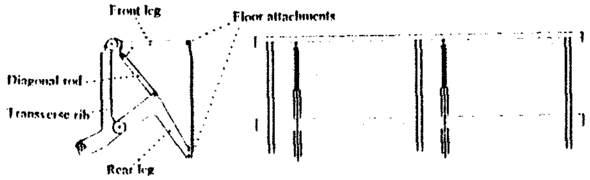


Fig.7

Originally the seat, designed for the old certification requirements, was not able to pass the new 16g and 14g crash tests mentioned before.

Structural failures occurred in the front leg (bending), the diagonal rod constraint (bolt shear fracture) and the transverse rib (shear fracture) in Test 2 and the compression load in the ATD lumbar spine exceeded the limits in Test 1. AVIOINTERIORS requested to improve the seat structure for certification without strong modifications of the original structure, to minimise manufacture costs.

The first VEDYAC models were intended to reproduce the failure patterns and load-time histories coming from experimental data acquisition made during the unsuccessful tests. The geometry of the structural model is shown in fig.8, together with the ATD structural model and a graphic presentation of the seat model

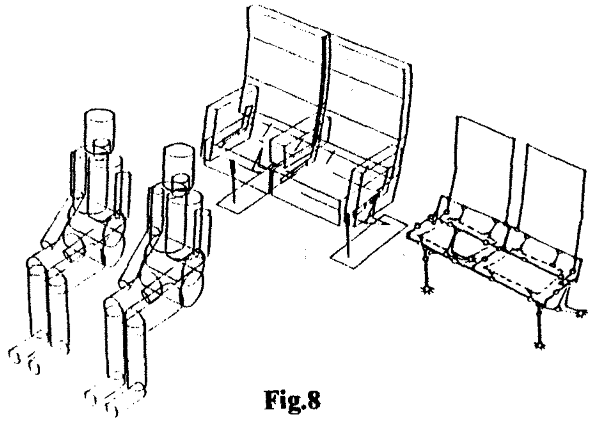


Fig.8

The mechanical properties (stiffness, plastic and rupture limits) of the deformable elements were obtained mostly by static testing on the main structural components of the seat and, in minor part, by analytical computation.

The mechanical properties of the cushion, which play a main role in Test 1, were instead obtained by dynamic testing using the drop tower described above: on the bottom of the sled a contact surface was installed to reproduce the shape of the ATD lower pelvis, because during pelvis-cushion interaction the force is function of the contact surface. The sled was dropped on the seat cushion obtaining the force-penetration plot. A VEDYAC model was developed to simulate this dynamic test (fig.9), calibrating the input data until a good agreement was obtained between the experimental and simulated force-penetration plots.

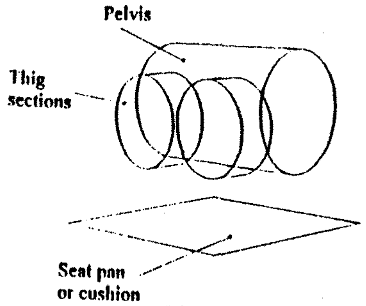


Fig.9

After validating the model of the seat, the modifications were first tested and investigated in the computer simulation and then applied to the seat prototype for experimental testing.

Actually the final solution was reached by consecutive seat model refinements, each time corrected and validated by the crash tests. The procedure adopted is described in fig.10.

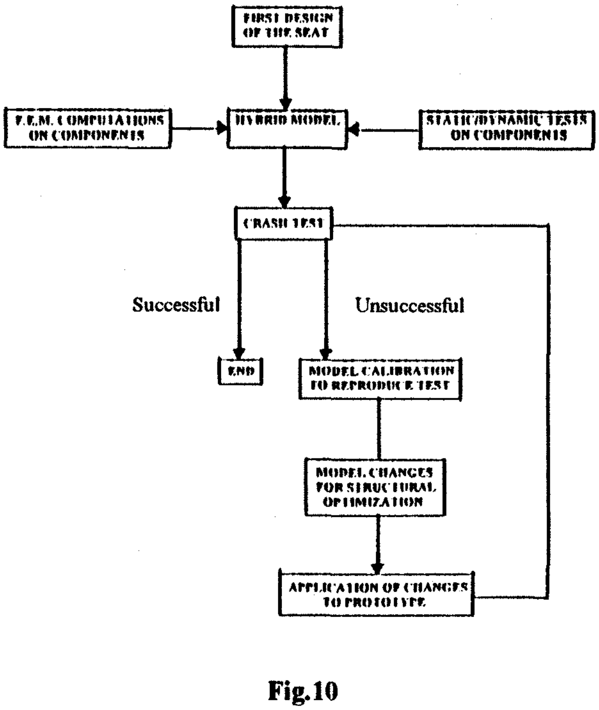


Fig.10

The computer model provided the time history of the internal loads in the structural components of the seat, thus giving a useful information for component dimensioning, cushion characteristics and geometry modifications.

In early 1994 the seat was certificated and is now installed on board of Airbus A340 of the French airline company UTA.

THE PROBLEM OF THE MOST CRITICAL SEAT CONFIGURATION

As mentioned before, the civil transport aircraft seat must be set up, in Test 2, in the most critical configuration, which must be chosen among 16 possibilities. The choice is not simple actually because there may be one critical condition for occupant injury (HIC, femur load), another one for seat-floor constraints, or for other seat components.

The Advisory Circular and the Aerospace Standard give no details about the choice of the seat worst case, and any "reasonable" deduction is hazardous due to the complexity of the seat-occupant structure and dynamics. The regulations encourage anyway computer simulation, provided the model is reliable.

In the present work the model was refined by several experimental testing. Every time 8 seat configurations were analysed (the floor roll deformation was not taken into account because the seat attachment had very low stiffness in that degree of freedom) and a table was filled with all maximum values of the internal loads in the most critical components of the seat structure. The final certification test was done on the two worst configurations indicated by the numerical simulation, that resulted to be:

1) yaw angle = 10° nose right
floor pitch = 10° nose up under left legs
floor roll = 10° clockwise under right legs
2) yaw angle = 10° nose left
floor pitch = 10° nose up under left legs
floor roll = 10° clockwise under right legs

In both cases there was satisfactory agreement between experimental and numerical results. Fig.11 and 12 refer to Test 2 and report respectively experiment-simulation comparison of load in one seat-floor fixture and one ATD head resultant acceleration.

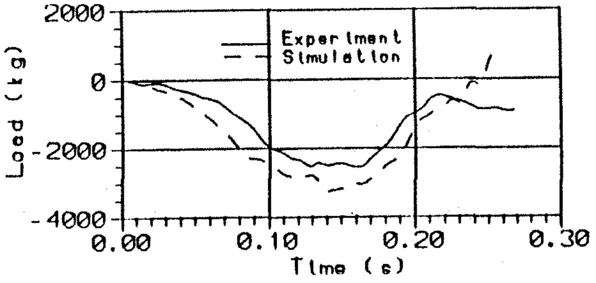


Fig.11

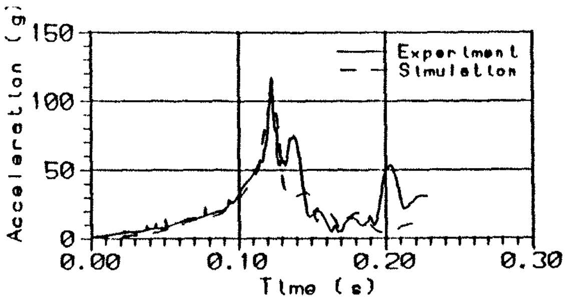


Fig.12

Fig.13 refers to Test 1 and shows both experimental and simulated load in one ATD lumbar spine.

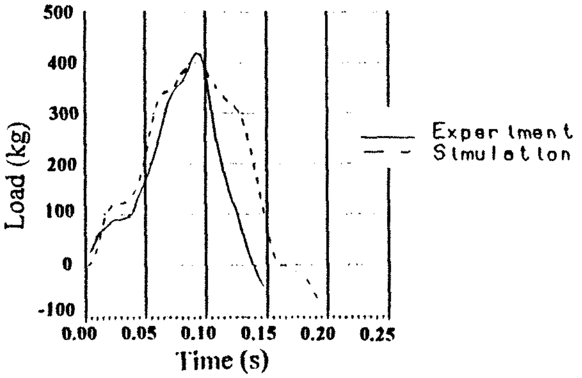


Fig.13

Fig.14 and 15 are sequences of animation plots coming from VEDYAC simulation, both for Test 1 and Test 2.

The use of numerical simulation to find the worst case configuration of a seat structure in crash testing is actually new, and in fact it requested a strong effort to make the italian aeronautical authorities to accept this procedure, but after the evidence of the simulation-experiment correspondence they simply requested a supplementary crash test in the second worst case configuration.

CASE 2: F22 PINGUINO SEAT

GENERALAVIA F22 "Pinguino", designed by Stelio Frati, is a propeller acrobatic trainer airplane, with two side-by-side seats.

The seat is a small and light structure connected to the aircraft floor. As shown schematically in fig.16, it is located above the wing spar, so that the clearance between the seat pan and the spar is more or less 12 cm. This is the total disposable seat stroke in case of emergency landing with prevalent vertical component of velocity, or during crash Test 1 that, for this category airplanes, consists in a 19 g's peak acceleration pulse.

Originally the seat was not designed on the base of crashworthy criteria and, in fact, the Test 1 and Test 2 were completely unsuccessful due respectively to a high load in ATD lumbar spine and pelvis submarining.

The problem of submarining was easily solved by changing the 4-point safety belts in a 5-point system.

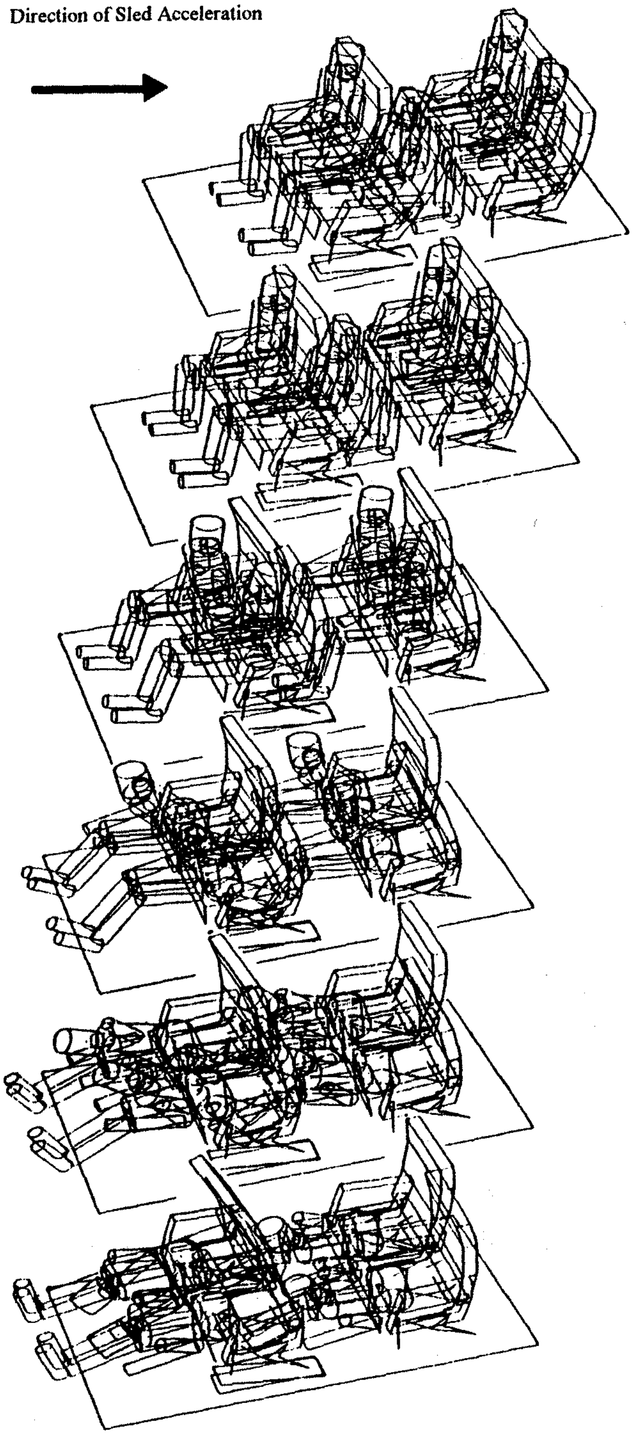


Fig.14

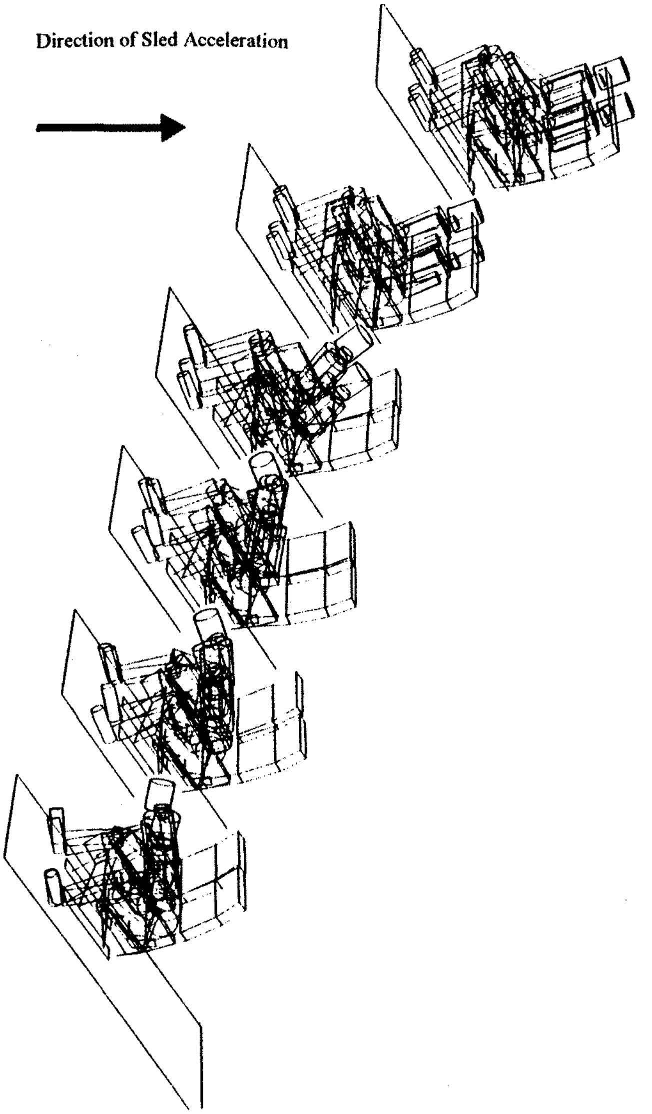


Fig.15

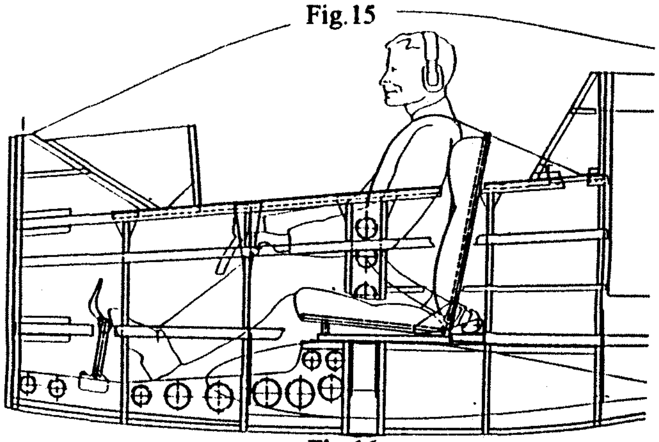


Fig.16

The high spine load was instead due to the material used in dependence of the reduced stroke under the seat pan. The seat was a rigid steel frame, with a thick and comfortable cushion above a polyurethanic foam in a aluminium box. The cushion was very soft and was deflected without any significant energy absorption. The boxed foam was too rigid and induced high contact forces to the pelvis with very small deformations.

Other solutions were tested, eliminating the soft cushion and using polyurethanic foams of different densities but the tests were unsuccessful. The typical force-deformation pattern of this kind of materials is plotted in fig.17. This plot was obtained in dynamic tests made with the drop tower, using the same procedure to test AVIOINTERIORS cushions, that is a sled, with a contact surface that reproduced the ATD lower pelvis, dropped on the seat pan made of two different foams.

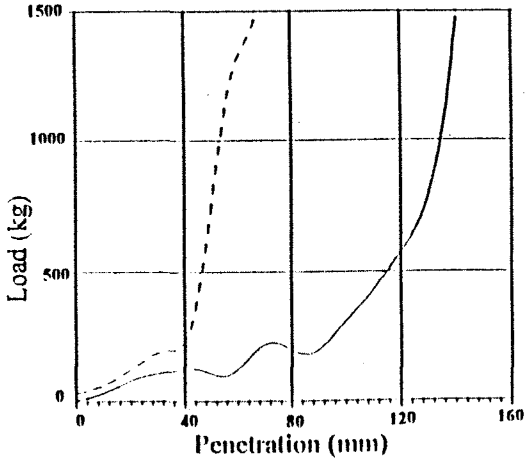


Fig.17

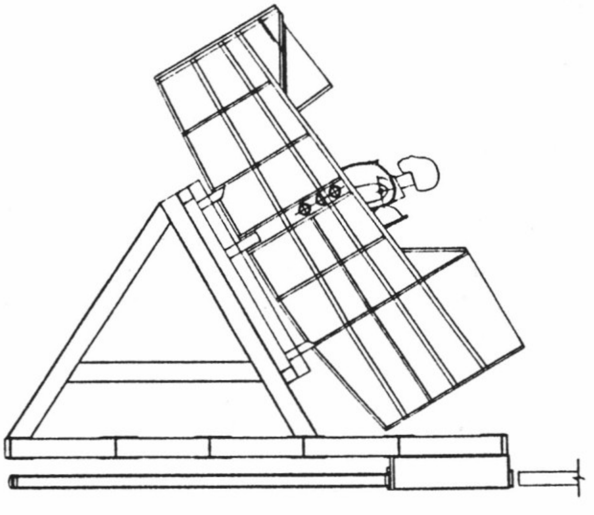
It is evident that such a dynamic behaviour has very low efficiency for energy absorption if compared to an elastic-plastic or, ideally, a rigid-plastic device. It was actually not evident that it was possible to reduce the main limbar load under the requested limit of 675 kg, even with high efficiency materials.

A VEDYAC model was set up of the cockpit, ATD and seat. Both the crash tests on the complete system and the dropping tests on the seat pan provided the data necessary to validate the model. After excluding the idea of using anything similar to a polyurethanic foam, it was evident that the only possible solution could be in a elastic-plastic seat.

The seat model was very simple, because the only rigid body was the seat pan, while the other parts were solid with the cockpit. Fig.18 reports schematically the crash test set up and the VEDYAC model. In the model the seat pan was connected to the cockpit floor with 4 straight deformable elements, or 4 legs, with elastic-plastic behaviour. A parametric analysis was performed by simulation using as variable parameters the stiffness and plastic limit of the 4 connections and as dependent variable the load measured in the lumbar spine of the ATD model.

The results are plotted in fig.19 and 20. They are a 3D and a topographic plot of the lumbar load versus leg stiffness and plastic limit, showing that:

1) the solution exists but in a restricted domain; the shaded area in the plots represents in fact the values for leg stiffness and plastic limit where the lumbar



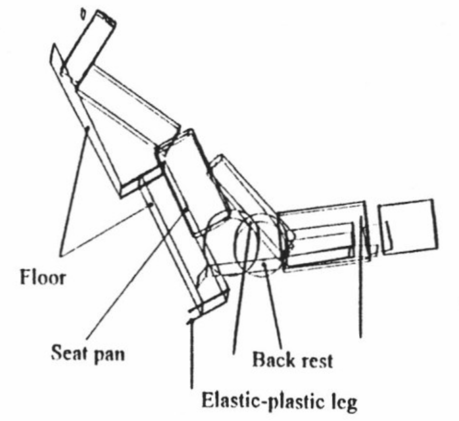


Fig.18

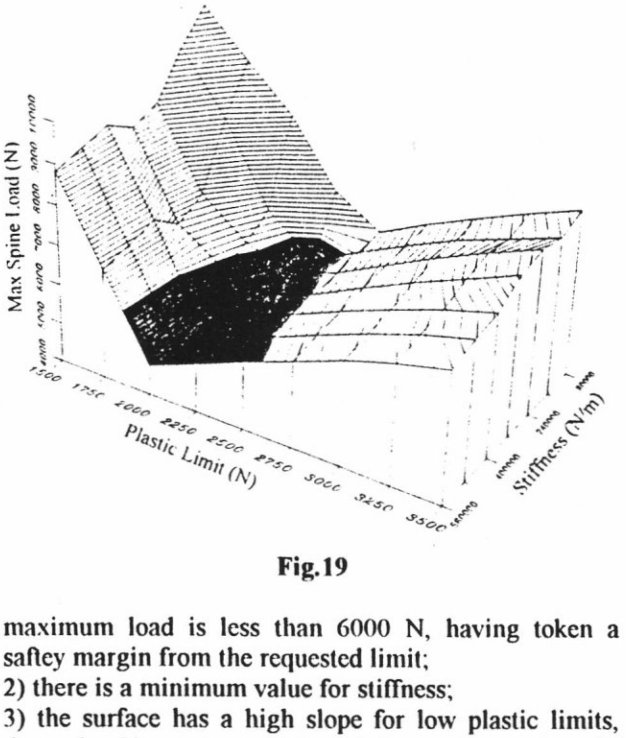


Fig.19

maximum load is less than 6000 N, having token a saftey margin from the requested limit;

2) there is a minimum value for stiffness;

3) the surface has a high slope for low plastic limits, determined by seat pan and pelvis bottoming against the cockpit rigid floor.

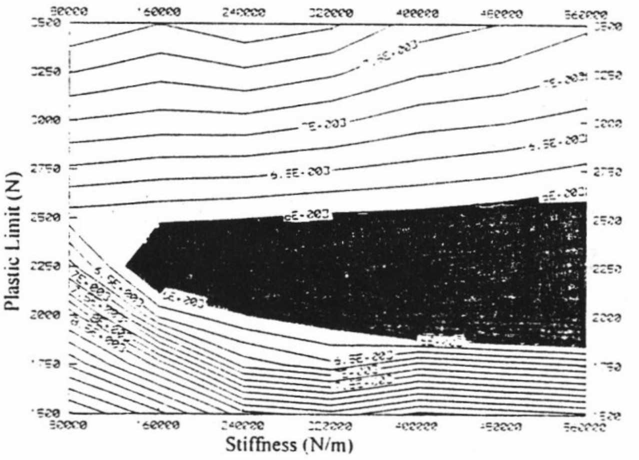


Fig.20

Therefore the 4 seat legs were designed with their mechanical characteristics around a point in the topographic plot with a high stiffness value and a plastic limit slightly higher than that of minimum spine load, to take some safety margin from the risk of bottoming. The solution is very simple, consisting of 4 semicircular metal tubes connected to the seat pan and to the floor.

First the seat pan was tested and calibrated under the drop tower and then the complete system was tested for final certification, at the end of 1993.

Fig.21 reports a sequence of plots coming from VEDYAC simulation of Test 1.

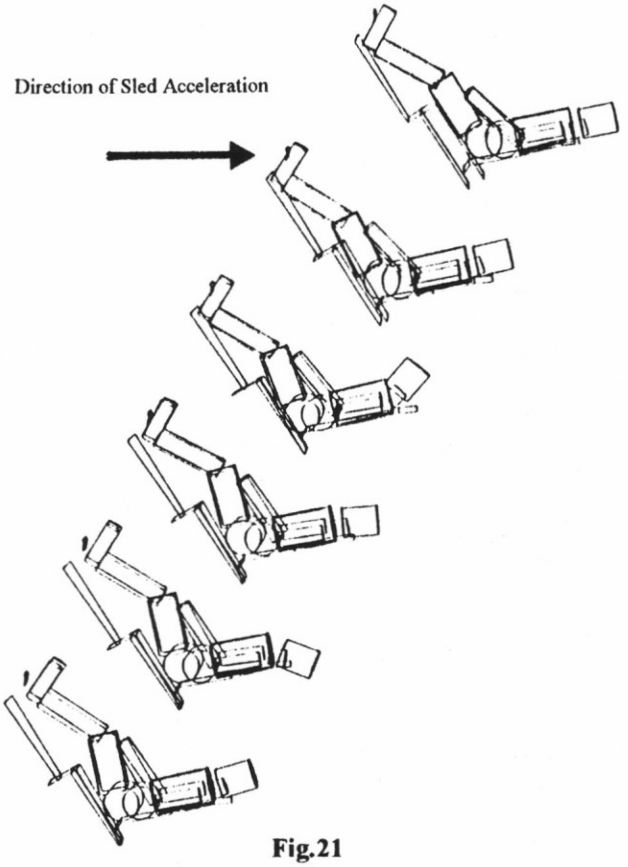


Fig.21

Fig.22 is a plot of the load in ATD lumbar spine, coming from experimental test data acquisition, VEDYAC simulation and MADYMO simulation.

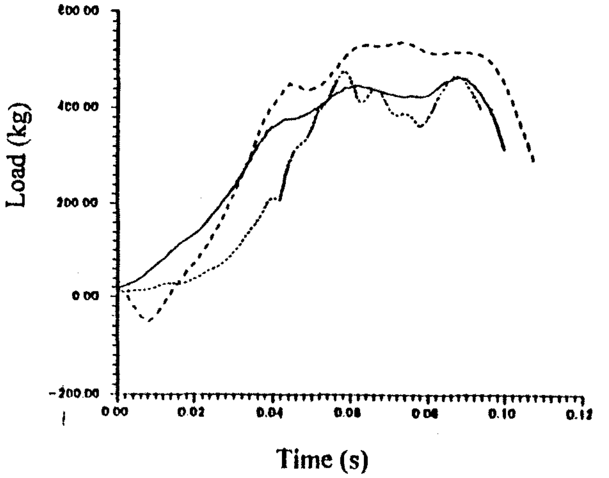


Fig.22

In this case the use of numerical simulation was essential first of all to find out the possibility of solution, and then to localise a feasible design point in the solution domain.

A parametric analysis is impossible by experimentation, for cost and time: one VEDYAC simulation, in this case, lasts less than 20 s on a HP RISC 735 Workstation, allowing to do in a short time a huge amount of computations. The parametric analysis described above is based on a grid of 9 stiffness values x 9 plastic limit values, i.e. 81 simulations.

CONCLUSIONS

The problem of the design of aircraft seats responding to the new crash regulations is assuming great interest, due to the severity of the test impact conditions now necessary to certification. At present only a few manufacturers in the world succeeded in that task, while most aircraft manufacturers demand for new certificated seats.

For the complexity of the seat structures and anthropometric test dummies dynamics, the most reliable method to improve the seat is, as usual, the experimental method, but times and costs should be prohibitive because a large amount of tests should be performed to optimise the seat structure for certification.

A significant contribution in design and calibration can be obtained by hybrid simulation. It cannot substitute experimental testing, which is moreover required by the rules for final certification, but can reduce the number of tests and therefore costs and times. Once a validated model has been developed for seat and occupant, any modification can be first studied in the numerical simulation and then adopted in the seat prototype for testing. This method also brings to a more accurate interpretation of the experimental results, thanks to its repeatability and the possibility of post-processing analysis.

The use of hybrid simulation also reduces the number of tests required to certificate a seat when a "most critical test configuration" must be chosen among many possible configurations. Actually the rules are plain as far as Test 1 is concerned, but the problem of choosing the worst floor deformation in Test 2 is complex and may easily lead to mistakes if the choice is not supported by a high level computational tool: a finite element simulation is too expensive in terms of mesh preparation and computing times; a hybrid simulation, integrated with experimental testing on minor structural components, is quick both in terms of mesh preparation and computing time and, if the lumped mass model is well discretised, it gives the necessary accuracy and detail.

Hybrid simulation moreover, thanks to its low computation time, allows a sensitive or parametric analysis for structure optimisation, which cannot be done by experimentation or finite element method.

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