CABIN SAFETY SENSITIVITY TO THE MECHANICAL PARAMETERS OF THE MAIN CRASHWORTHY STAGES

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Abstract

Crashworthy helicopters have energy absorbing concepts introduced into seats, subfloor and landing gears. These stages are always passive systems, usually triggered by a load level, and develop pre-set responses independently from the crash speed. Moreover, the different stages are usually studied as single components, without considering the mutual effects and any possible integration.

This study is based on a lumped mass numerical model of a representative, but very simplified, rotorcraft section, including the three crashworthy stages of landing gear, subfloor structure and seat with anthropomorphic dummy. A series of analyses show the advantages, in terms of accident survivability, associated to a seat and landing gear with mechanical characteristics optimised according to varying impact velocities.

1. INTRODUCTION

During a crash landing, high loads are transferred into the cabin and, more in general, to different areas of the rotorcraft structure. The main hazards for the occupants are associated to direct loads from the seat and restraint system, impact of flailing body segments against the surrounding surfaces and intrusion of external objects such as rotor blades, engines and transmission gearbox.

All these effects can be mitigated by proper crashworthy design, which has been introduced in modern helicopters.

Seat, subfloor and landing gear are three essential elements in this design; they are particularly effective during a levelled attitude crash landing, which is a frequent condition for helicopter ground accidents. These elements, if properly designed, can be seen as a series of energy absorbers located between the ground and the occupant.

As a matter of fact, the crashworthiness of these three stages has been deeply studied in the last decades and both recommendations[1] and regulations[2] have been issued to drive the design and the performances assessment.

Nevertheless, in most cases the studies are focussed on the single stages and do not consider their mutual interactions.

The basic idea of this paper, on the opposite, is that their mutual interaction could be exploited to reduce occupants' injury levels, or to extend the survivable velocity envelope. A lumped mass numerical model is used to analyse the mechanical parameters of seat, subfloor and landing gear and their influence on the lumbar spine load. In particular the parametrical analysis is focussed to demonstrate that the limit of 9.15 m/s, used in one of the dynamic tests of the seat, can be easily exceeded if the three energy absorbing stages are optimised as a set rather than individually, and the best results are obtained if adaptive systems could be introduced that tailors the mechanical characteristics of the crashworthy stages to the impact conditions.

Before focussing on the parametrical problem, a quick description of the crash scenario considered in this study and the crashworthy stages is carried out.

2. CRASH SCENARIO

Although the crash landing conditions of an aircraft are in general unpredictable, some accident statistics survey has been carried out in the past years[3], to find out the most typical crash conditions.

These studies suggest that, for a rotorcraft, a high accident percentile occurs with limited angles of roll, pitch and yaw; in other words, a levelled attitude condition can be considered representative for a crash landing.

Concerning the speed, roughly 65% of the crash landings occur with a longitudinal speed lower than 1.5 m/s, and 90% with a lateral speed lower than 1.5 m/s.

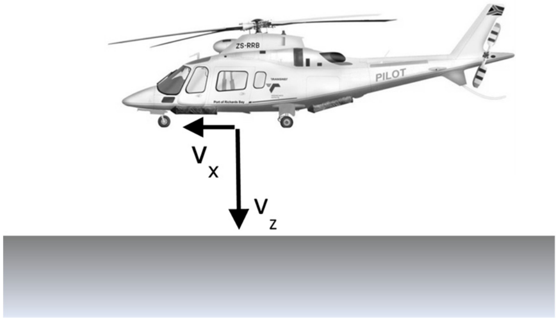

Fig. 1 - Crash landing condition with vertical (v_z) and longitudinal (v_x) velocity components

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Basing on these considerations, a levelled attitude vertical drop like that one shown in fig. 1 could be an interesting, as well as simplified, starting point to investigate the contribution of crashworthy stages to occupants' injury attenuation.

Considering a longitudinal speed component up to of 9 m/s would extend the statistical percent from 65 to 90%, but this would significantly complicate the analysis; this component would in fact introduce into the vehicle a longitudinal load, function of the ground friction, and possible ploughing[1] if one considers a soft soil impact, with risk of rollover or at least increase of the pitch angle.

For the sake of simplicity this study will then focus on a levelled attitude vertical drop of the vehicle, leaving a possible extension on longitudinal speed to further developments.

3. ENERGY ABSORBING STAGES

During a crash landing with high vertical components of velocity, the main injury risks for the occupants derive from the dynamic loading of the spine and intrusion of upper masses, like engines and gearbox.

The introduction of a crashworthy landing gear and subfloor mitigates both the cabin acceleration and the overall structural loading, then reducing the risk of engines and gearbox fixture failing and cabin intrusion; a crashworthy seat will concentrate the effect on occupant's injury mitigation. In particular this paper will focus on the lumbar spine load attenuation obtained by the three crashworthy stages of seat, subfloor and landing gear. The lumbar spine load is in fact considered a relevant marker for cabin safety, when a vertical acceleration is considered. Moreover, the measure of this load with an anthropomorphic test dummy is mandatory for seat certification testing[2,3].

3.1. Landing gear

At levelled attitude, the landing gear, when extracted, is the first component impacting the ground.

In non-crashworthy landing gears, the shock absorber reaction is made of a polytropic response associated to the compression of a nitrogen chamber and a viscous response associated to the oil flowing through one or more orifices. The area of these orifices can be metered by valves, as shown in fig. 2. Usually a spring-loaded poppet valve with fixed orifices can be sized to give differential damping characteristics during strut extension and compression, ensuring optimal compromise between simplicity, reliability and energy absorption capability. The valve poppet is normally closed and preloaded by the valve spring. During landing, shock absorber compresses and oil flows through the orifice, building up pressure. When pressure reaches the spring threshold, the poppet opens and creates a higher oil flow passage, hence reducing excessive further pressure build-up.

During a shock absorber extension, the poppet is maintained closed by the spring preload, oil flows through the fixed orifice in the reverse direction, pushes the recoil valve and opens it. Shock absorber extension speed is therefore adjusted to prevent rebound.

This solution is commonly adopted in all aircraft categories and increases the shock absorber efficiency, defined as the ratio between the absorbed work and the max work given by the max reaction and the max deflection.

In other words, the valve plays the role of softening the viscous peak when the landing gear is compressed with a high velocity.

The landing gears are qualified against drop tests with sink speed in the range 2-3 m/s. The valve is activated normally when the shock absorber rate is in the range 1-2 m/s, granting high efficiencies within

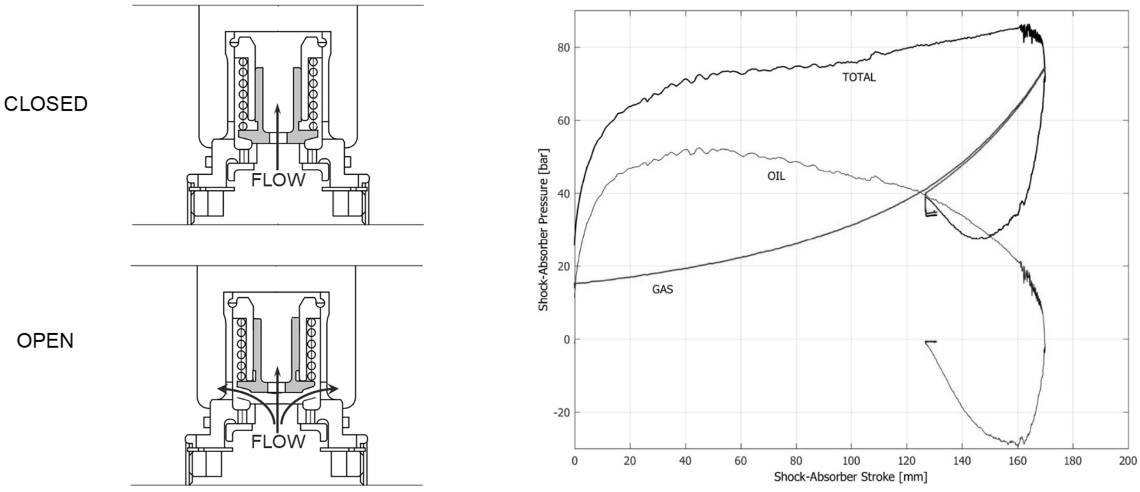


Fig.2 – Landing gear metering valve and typical reaction in normal landing conditions

this range and acceptable efficiencies up to 3 m/s. This means that, in a typical crash landing condition, where vertical speeds are higher than 3 m/s, the viscous peak is not significantly attenuated and increasing loads are transferred to the structure.

Because the pressure is quadratic with the flow rate, and then with the shock absorber rate, the total reaction generated by the shock absorber can easily reach the strength of the landing gear fixtures, which could be broken away before the full stroke of the shock absorber is exploited.

A landing gear can then be equipped with a crash stage[4,5,6], which anyway requires an extra stroke, or with additional valves in the shock absorber that are activated when high pressure drops are reached[7], further attenuating the viscous peak during the stroke.

This second approach is selected for implementation in the present numerical study. The shock absorber will then be modelled parameterising the viscous response in a way that is technologically feasible, i.e. by changing the outflow orifices.

3.2. Subfloor

The helicopter subfloor normally starts working after the landing gear breaks away; if this is not extracted, the subfloor becomes the first structural components impacting the ground.

This area has been taken into consideration for the past 20 years as an effective crashworthy system. Its geometry favours the introduction of energy absorbing concepts: it is a frame of longitudinal and transversal beams that transfer the load between the lower external skin and the internal floor. The intersections between the beams can be very stiff in compression and are usually weakened to trigger a buckling response without transferring an overload to the cabin floor[8,9,10].

Fig. 3 shows a typical subfloor structure and the response under dynamic compressive load obtained at Politecnico di Milano for an intersection element designed for a helicopter subfloor and based on riveted thin aluminium alloy sheets. Usually a first buckling load peak is observed in this kind of structural component, corresponding to the triggering of the first fold; then the development of successive folds is associated to smoother fluctuations of the load vs. deflection, followed by a steep load increase associated to the final metal sheets compacting. A crashworthy subfloor should then have a low initial load, which may be obtained by pre-triggering the structural components, and maintain the deflection within the limit of the final load increase

3.3. Seat

Civil helicopter seats must be certified against an experimental test with a 30 g's peak load, with dominant velocity along the vehicle yaw axis; the seats must then be equipped with energy absorbing devices, usually located between the seat buckle and a couple of tracks connecting it to the subfloor.

Several types of absorbers have been used for the helicopter seats, but the most common one is based on a metal tube that is forced to pass through a couple of rollers; since the tube outer diameter is lower than the rollers clearance, the tube is ovalised and develops a force that, after a first rise stage, is constant. Fig. 4 shows a typical 30° attitude test set-up including a sketch of the system and some results obtained at Politecnico di Milano from dynamic experimental testing on some samples, after manufacturing an ad hoc test rig where the rollers clearance was adjustable. The influence of this clearance on the load level is significant, which suggests the possibility to develop a smart energy absorber based on the rollers position control.

These results were obtained with an ASTM A213M-14 TP304 steel tube, with 10 mm outer diameter and 1.5 mm thickness.

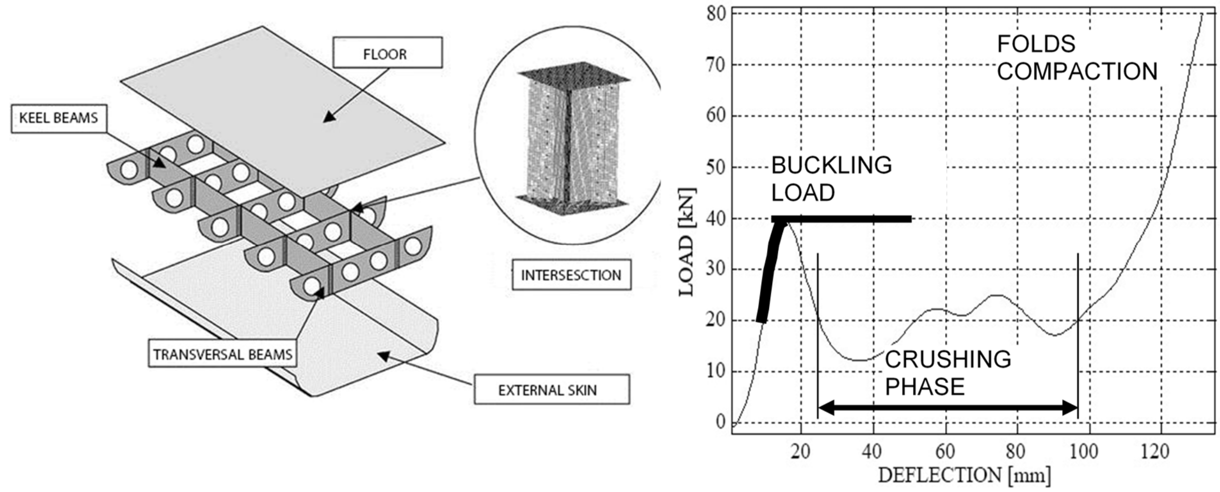


Fig.3 – Subfloor architecture and typical load vs. deflection response of an intersection element

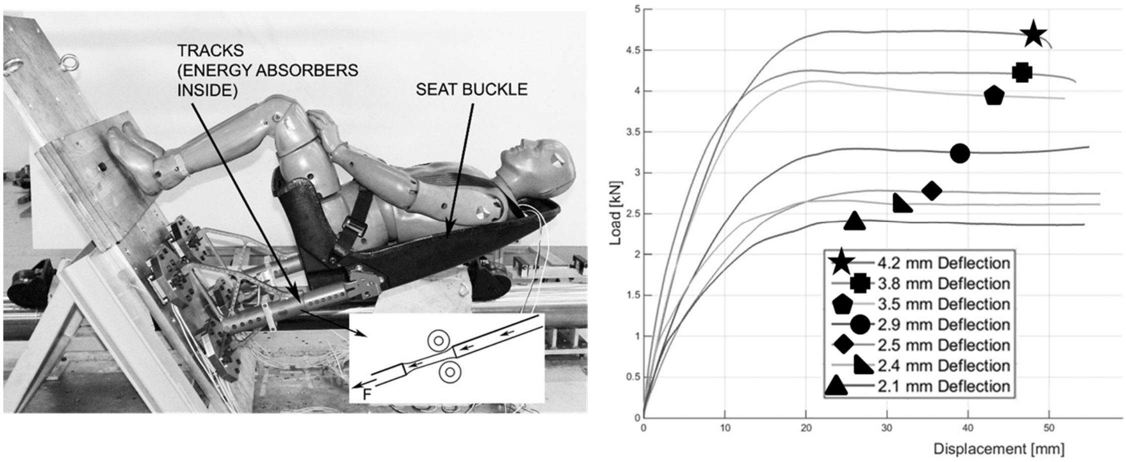


Fig. 4 – Seat energy absorber load vs. stroke, variation as a function of rollers clearance: the deflection indicated in the legend is the diameter reduction induced in the tube by the rollers clearance

4. LANDING GEAR PRELIMINARY STUDY

The landing gear is first modelled with VI-Aircraft, version 15, an engineering environment for the simulation of aircraft derived from MSC-ADAMS, specially oriented to landing gear and ground vehicle handling simulation. Rigid parts, joints and the other components are derived from the 3D model of the landing gear system. Fig. 5 shows the landing gear model, which is made of 6 rigid parts: upper cylinder, lower piston, anti-torque (2 bodies), wheel and drag brace link.

This software was here used for a preliminary setting of parameters. The shock absorber is modelled as a double-stage airspring with separation between oil and air. The first stage is serviced at low pressure and works in ground manoeuvre operation and landing at low sink speed; the second stage is serviced at high pressure and is active only during landing at higher sink speed.

Oil damping effects and bearing friction are represented in the model. In particular, a fixed orifice response works at low shock absorber rates (i.e. in normal taxi run and ground manoeuvre operation); then a two-stage spring-loaded fixed orifice is modelled for different landing purposes: the metering valve with first stage spring-loaded fixed orifice works in normal landing conditions; a second stage spring-loaded fixed orifice is triggered by higher sink speed, or crash landing conditions. Recoil orifices are used du ring extension to control shock absorber extension speed and prevent rebound.

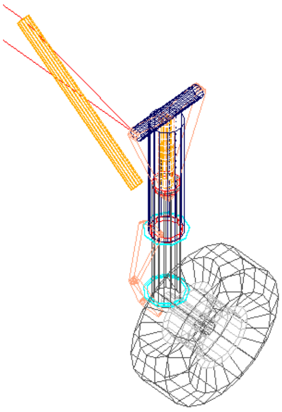


Fig. 5 – Main landing gear VI-Aircraft model

Tire is introduced by simulating the vertical load and deflection characteristics and by considering its inertial properties. The load oscillation due to tire spin-up process can be simulated in the model when dropping on a flat surface.

Final tuning of the shock absorber characteristics was a compromise among different requirements: stroke around 65% in static condition, high pressure chamber not working in static condition, high efficiency in limit landing and limited load factor in a 10 m/s crash landing.

Fig. 6 shows the polytropic reaction as a function of shock absorber stroke and viscous response as a function of shock absorber deflection rate. They are referred to a 6000 kg helicopter, which is considered in this study.

5. FULL NUMERICAL MODEL

The numerical model developed for this study is based on MuSIaC – Multi-Scale Impact and Crash, a code developed at Politecnico di Milano with a lumped parameters formulation. This choice, with respect to finite element approach, was determined by two reasons: first of all, an energy absorbing seat and an anthropomorphic test dummy were already available and validated against a series of

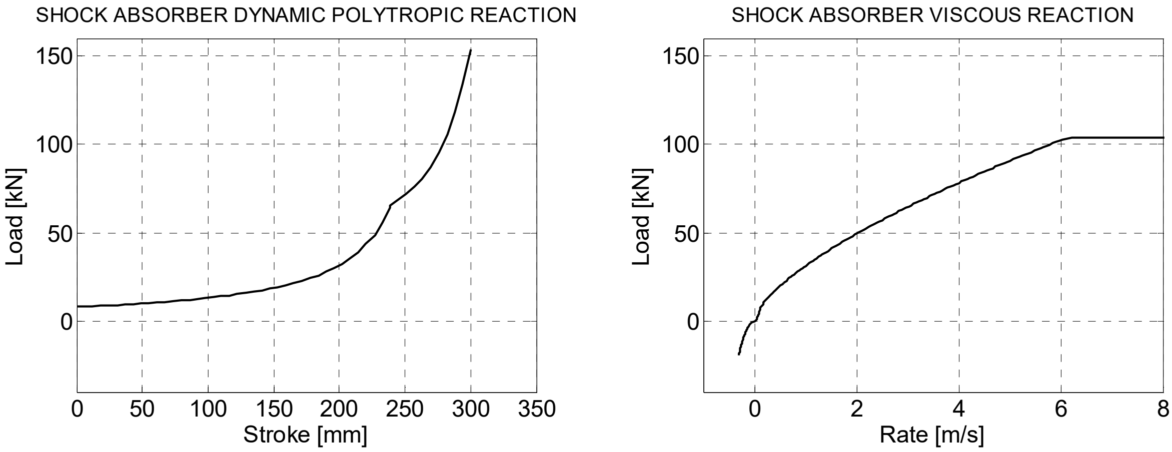


Fig.6 – Shock absorber polytropic and vicous reactions

experimental data[10]; second, a lumped mass approach is more efficient than a finite element approach, in terms of CPU time, when a parametrical analysis is needed, if the related loss of precision and detail is affordable.

The model is very simplified and is made only by those sections of the helicopter structure which include the main landing gear, a relevant subfloor volume and the seat, with the anthropomorphic test dummy seated and restrained: Fig 7 shows the model in its initial conditions, above the ground and with an initial vertical velocity, followed by a sequence of the most meaningful frames representing the system dynamics. The first component involved is the tire, which starts deflecting and transfers the reaction to the shock absorbers; the shock absorbers are compressed following the polytropic and viscous pattern, till the pin limit load is reached: this may happen either if the viscous reaction is high or if the shock absorber max stroke is reached; then the subfloor impacts the ground and starts crushing; if this crushing load is high, this may trigger also the seat energy absorbers; otherwise the seat starts sliding after the subfloor has completely crushed.

Starting from bottom to top, the landing gear is made of thee rigid bodies: the wheel, the lower shock absorber (piston) and the upper shock absorber (cylinder). The wheel is connected to the lower shock absorber by a free rotational joint; the piston is connected to the cylinder by a translational joint and has got an internal reaction that is a table function of the shock absorber stroke and stroking rate.

The upper shock absorber is connected to the helicopter by a series of joints representing the main strut pins and the stay pin.

The helicopter fuselage is here represented only by the belly skin and a subfloor section; the mass is lumped in the belly and the moments of inertia are artificially increased to avoid any rotation during the dynamics. The subfloor is a box made of a section of belly skin and a section of cabin floor, connected each other by a set of 4 beam elements, which represent the subfloor deformable beams and intersections.

The seat is a 2-rigid body system representing the lower tracks attached to the floor and the upper seat buckle; they are connected each other by means of translational joints representing the energy absorbers and sliders.

Finally, the anthropomorphic dummy is a 17-rigid body system validated in previous works with a rigid seat as well as with the above-mentioned crashworthy seat model, against a series of experimental tests.

6. DEFINITION OF PARAMETERS

A set of parameters can be selected to define properly the contribution of the different stages to energy absorption and occupant injury risk

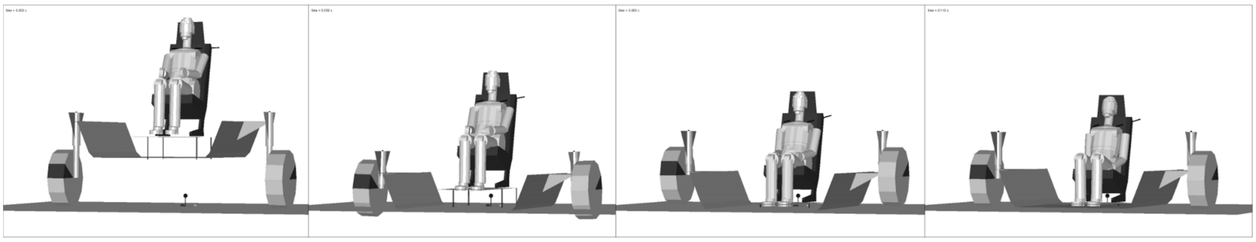


Fig.7 – Frame sequence from a dynamic analysis: A) initial condition, B) MLG shock absorber fully compressed, belly impact, C) MLG has broken away and subfloor stops crushing, D) seat stops sliding

assessment.

These parameters are here selected with an eye to the possibility to implement smart systems, which could adapt to the crash conditions.

The ranges here described are related to a 6000 kg helicopter.

6.1. Landing gear parameters

The dissipative component of the shock absorber is the oil flow. Therefore, the polytropic reaction is fixed and equal to that one shown in previous fig. 6, while the viscous reaction is parameterised.

After some preliminary analyses, and to limit the number of variables, it was decided to scale the curve shown in fig. 6 along the vertical axis; this means that the 6 m/s limit, after which the reaction flattens, is maintained. The most interesting results are obtained by scanning a range between 100% and 600% the reference reaction, limiting the shock absorber stroke to 300 mm, as seen in fig. 8A. The landing gear position with respect to the dummy helicopter body is fixed to have the shock absorber bottoming a few mm before the subfloor ground impact, also considering the tire deflection. Moreover, the landing gear attachments points to the helicopter body are made breakable at a load given by the sum of the max polytropic response and the max viscous response. This means that, when the sink speed is high enough to bring the shock absorber at full stroke, the landing gear attachments break away and the subfloor impacts to ground.

6.2. Subfloor parameters

The subfloor response is approximated in this model as a perfect elastic-plastic reaction in the axial degree of freedom of the 4 beam elements representing the internal subfloor structure: the crushing load corresponds then to the plastic value of the beam element.

Considering fig. 8b, a range from 4.0 to 7.0 kN for each beam element is analysed in this study; nevertheless, a subfloor could be hardly designed and manufactured as a smart or adaptive system; therefore, this parameterisation has only the goal to determine the subfloor strength that better responds to the range of impact velocities that will be later considered in this study, developing a usable crush deflection without bottoming out.

The subfloor stroke before bottoming out is set at 200 mm.

6.3. Seat parameters

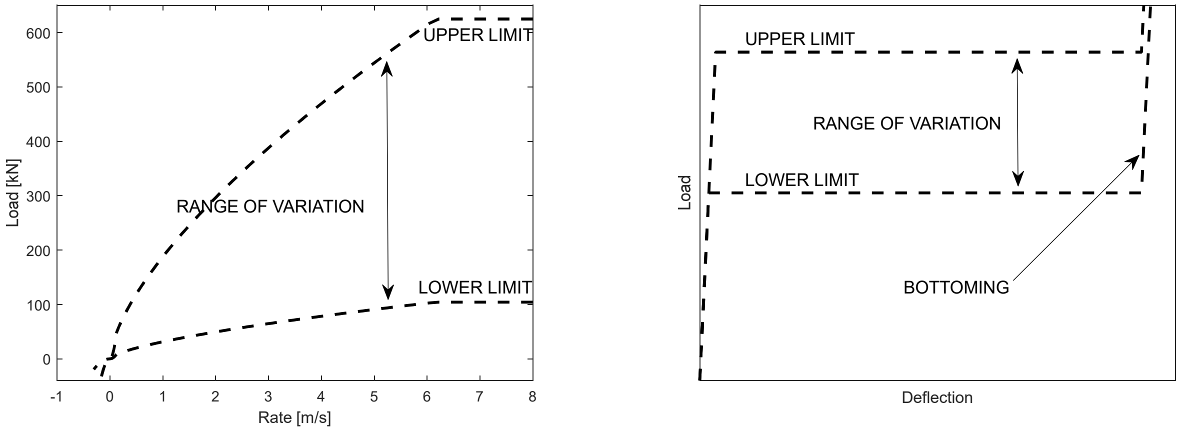
As already mentioned before, the seat energy absorbers load levels could be enough easily controlled by metering the roller clearance.

The model used in this study has one single energy absorber in the symmetry plane of the seat, then concentrating the response of the couple of absorbers normally installed on the helicopter seats. The load level is analysed in the range 6-16 kN shown in fig. 8b, then representing a 3-8 kN range for a typical double energy absorber system.

The max seat stroke before bottoming out is set at 200 mm.

7. RESULTS

As initial conditions the system is set with a vertical velocity at levelled attitude with the tires almost touching ground. A series of analyses are run increasing the impact velocity and changing the parameters within the ranges above indicated, evaluating their influence on the lumbar spine load, seat stroke and subfloor deflection. To define a sort of survivable region, the max allowable lumbar spine load is set at 6670 kN, according to the reference



A B

Fig.8 – Parameterisation A) of the shock absorber viscous response and B) of the generic elastic-plastic response used for subfloor crushing and seat energy absorbers

standards on seat certification.

After running all the analyses, the subfloor best design point was found to be with a crushing load around 5.5 kN in each of the 4 beams: higher values bring to generally higher lumbar spine loads; on the opposite, lower values bring to acceptable levels of spine load, but these areas are surrounded by wide zones with a steep spine load gradient, due to frequent seat and subfloor bottoming out conditions, then reducing the safety margin.

The results can be summarised by the response surfaces shown in fig. 9: in these graphs the max lumbar spine load, seat stroke and subfloor deflection are plotted against the seat energy absorber load level and the amplifying factor for the landing gear shock absorber viscous reaction; the

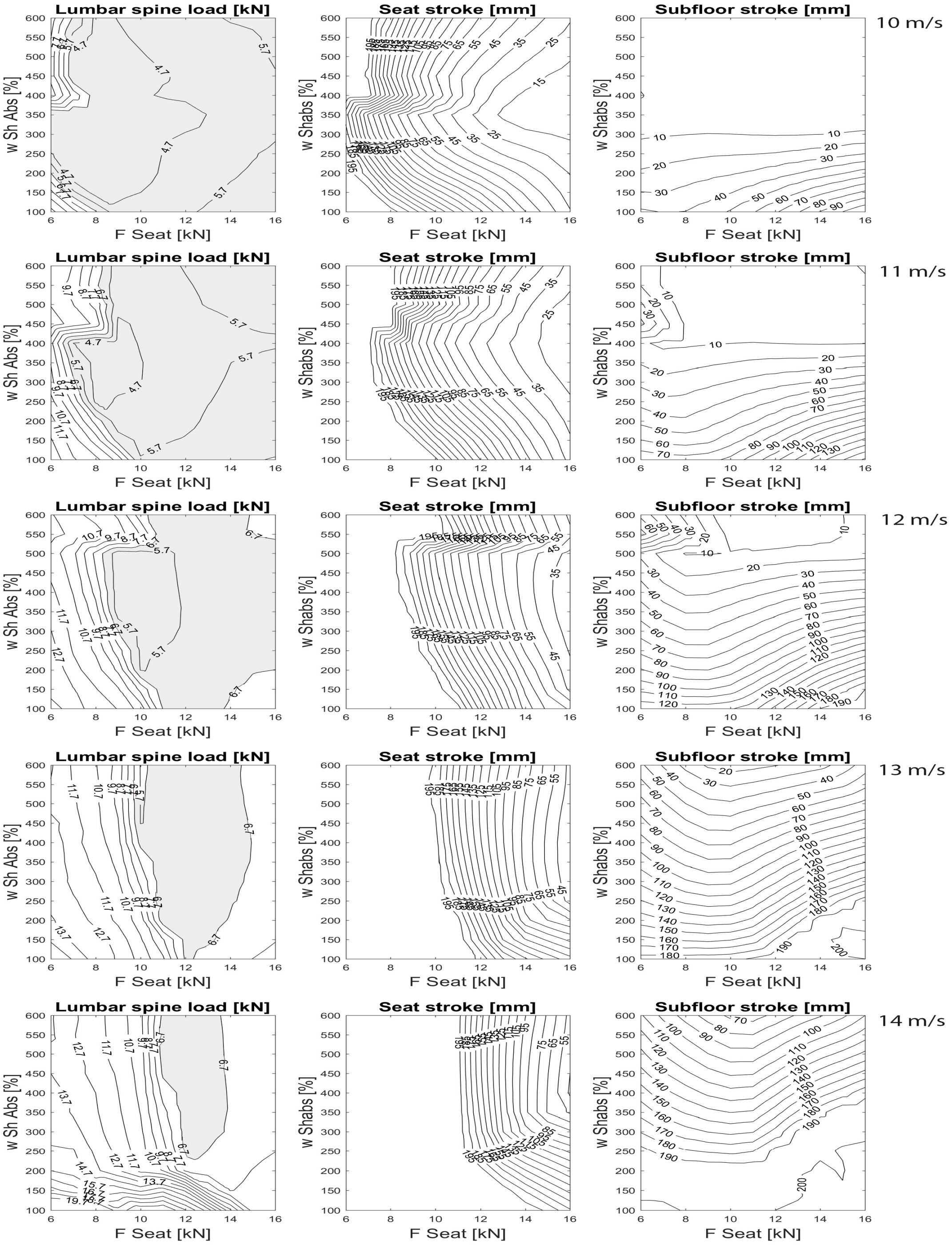


Fig.9 – Response surfaces of lumbar spine load, seat stroke and subfloor deflection vs. seat energy absorber load and shock absorber load, at different impact speeds

subfloor crushing load is frozen to 5.5 kN for each of the 4 beams.

The survivable region is that one within the 6.7 kN isoline. Moving from the safe region to the left, the surface gradient is high, because seat bottoming occurs; moving to the right, the increase of lumbar spine load is softer because it is due to a gradual hardening of the system.

It can be seen that at 10 m/s there is a wide survivable area where neither the seat or subfloor is deformed, meaning that the landing gear is able to absorb completely the impact energy.

By increasing the impact velocity, one can observe that the survivable region shrinks and moves slightly towards the upper right-hand corner of the figure, i.e. harder seat energy absorbers and harder landing gear shock absorbers; in the same time the surfaces describing seat stroke and subfloor deflection show a general increase.

A survivable region can be also found at 15 m/s, but it is very limited.

The migration of the best design point towards the upper right-hand corner of the figures can be easily understood. The increase of the impact velocity introduce a more severe seat stroke and then a higher risk of bottoming out, which can be contrasted by increasing the energy absorber response; the landing gear shock absorber is also very sensitive to the sink speed, being the viscous reaction a squared function of it; nevertheless this reaction is flattened after 6 m/s and then, to prevent landing gear bottoming, it must generate a higher reaction.

8. CONCLUSIONS

The main results achieved by this study are, on one hand, the possibility to increase the survivable impact velocity in a civil helicopter crash landing, by harmonising the optimisation of the energy absorbing stages, and on the other hand the numerical approach used.

As a reference one must consider that, for seat dynamic certification in civil rotorcraft, the impact is carried out at 9.15 m/s (actually the velocity component along the yaw axis is less than 8 m/s, due to testing seat attitude); therefore, the value of 14 m/s as max survivable impact speed should be considered a significant achievement.

There are two possible techniques to implement the results: passive and semi-active implementation. The passive implementation would consist in selecting the design point basing on the highest impact speed of 14 m/s; by setting the design parameters of the seat energy absorber and landing gear shock absorber at this point, crash landings with lower impact speeds result still survivable, even if the lumbar spine load is not minimised.

The semi-active implementation would consist in introducing adaptive systems in the seat energy absorber and landing gear shock absorber, which pre-set the devices basing on the impact velocity; this would of course require a trigger based on proximity and vertical speed sensors. In this case the lumbar spine load should be minimised in all impact conditions.

The numerical approach used for this study is based on a lumped mass technique; this kind of approach was very popular in the 90’s, when the computational power was not as high as today; nowadays finite element methods are more commonly used. Nevertheless, the high number of numerical analyses, requested to generate the surface responses, made the lumped mass approach more efficient: the CPU time for one single analysis is less than 15 s on a low-cost personal computer, meaning that in a few hours the response surfaces, based on 850 numerical simulations, are generated for each impact speeds.

Of course, if the subfloor available thickness, seat energy absorber stroke and landing gear stroke are different than those considered in this study, the best design point should be recalculated.

As a matter of fact, this study suggests that the optimal viscous reaction of the landing gear is in a range of high values, meaning that the landing gear breakable attachments to the rotorcraft (and surrounding structure) should be significantly oversized, with respect to a standard crashworthy landing gear configuration, with a consequent weight penalty.

This consideration opens other possible directions of investigation: for instance, the effect on weight penalty of introducing a thicker subfloor associated to a lower landing gear shock absorber stroke.

The subfloor is actually a critical question in helicopter crashworthiness. In this paper an internal subfloor was considered, i.e. a subfloor which crashes under the dynamic loading coming from the seats and occupants. This of course means that rotorcraft occupancy will influence the local subfloor crushing, with an effect in the surrounding areas; in other words, a subfloor section under an occupied seat may crush differently if the adjacent seats are occupied or free. This sensitivity to occupancy may be reduced by considering an external subfloor[12], which crashes under the dynamic loading of the overall rotorcraft structure. At any rate, the results obtained in this study should not change significantly if an external subfloor was considered, once the subfloor parameters are re-tuned in a new range of variation.

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