TWENTYFIFTH EUROPEAN ROTORCRAFT FORUM

Paper n° G12

# MULTI-BODY SIMULATION OF A HELICOPTER LANDING WITH SKID LANDING GEAR IN VARIOUS ATTITUDE AND SOIL CONDITIONS

BY

C. CAPRILE, A. AIROLDI, A. BIAGGI, P. MANDELLI

SEPTEMBRE, 14-16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

# MULTI-BODY SIMULATION OF A HELICOPTER LANDING WITH SKID LANDING GEAR IN VARIOUS ATTITUDES AND SOIL CONDITIONS

C. Caprile*, A. Airoldi*, A. Biaggi **, P. Mandelli
**Aerospace Engineering Department – Politecnico di Milano, Italy*
*** AGUSTA, Un'Azienda Finmeccanica - Italy*

## Abstract

A skid landing gear multi-body model is presented. Plastic bending deformations of structural members, dampers behaviour and the characteristics of the attachments with fuselage are reproduced.

Simulations of landing in horizontal level attitude, landing with drag and landing with lateral loads conditions are carried on with VeDyaC, an explicit multi-body code developed at Aerospace Engineering Department of Politecnico di Milano, and compared with experimental results. A good correlation between numerical and experimental data is achieved with regard to the landing performance, the loads transmitted to the fuselage and the strain state in the elastic spring members.

Simulation in various attitudes and soil conditions were performed and the sensitivity to soil friction factors was investigated. After the validation of the model, the work indicates VeDyaC, and generally, multi-body modelling, capacities to predict landing performance not only in emergency landing conditions, but also in limit conditions with the required accuracy.

## 1 - Introduction

Skid landing gears are characterised by a structural energy absorbing mechanism, which relies upon the deflection of their cross members, usually circular light alloy tubes, connecting the skids to the fuselage. In hard landing, yielding of these members is in most cases needed and allowed by regulations to fulfil prescribed limits on the helicopter load factor by increasing the landing gear efficiency [1]. As a consequence, plastic bending of cross members largely influences the performance of the landing gear in limit conditions.

The typical design methodology is based on the separate modelling of both forward and rear cross member, taking in account plastic bending [1]. An iterative algorithm can be used to evaluate the cross member load-deflection curves, thus leading to the information needed to predict the overall landing performance.

As cross members are considered separately, this classic approach has an intrinsic limitation in predicting the performances in non-horizontal landing attitudes. Moreover, some not uncommon features of skid landing gears, such as inclination of cross members, the presence of viscous dampers and contact phenomena between cross members and fuselage, introduce difficulties in a non-linear static evaluation of load-deflection curves.

These limitations can only be overcome by developing a complete model of the landing gear. The model should attain a reliable prediction of landing performance and of structural loads in different attitudes and soil conditions. The time required for modelling and solving should be kept as limited as possible in order to develop a tool of valuable utility both in the design and in the analysis phases.

Following these considerations a skid landing gear was modelled with a multi-body approach. Solutions were carried out with VeDyaC, an explicit multi-body code developed at Department of Aerospace Engineering of Politecnico di Milano [3, 4]. VeDyaC has been yet successfully used to model full-scale helicopter crash landing [5, 6, 7]. In this case the multi-body approach was directed to simulate accurately the landing performance in limit conditions with the aim to validate its capabilities in predicting, with the required precision, all the data useful to improve the insight in gear behaviour and gear interactions with fuselage. Moreover, the validate landing gear model is now available for crashing landing condition simulation.

## 2 - The Skid Landing Gear and the Model

The cross members of the skid landing gear taken into consideration are 7075-T6 aluminium alloy hollow tubes, with variable outer diameters. The forward and rear members differ in respect of dimensions, constraints to fuselage and features. Cross members planes are slightly inclined with respect to the helicopter yaw axis (Fig. 1).

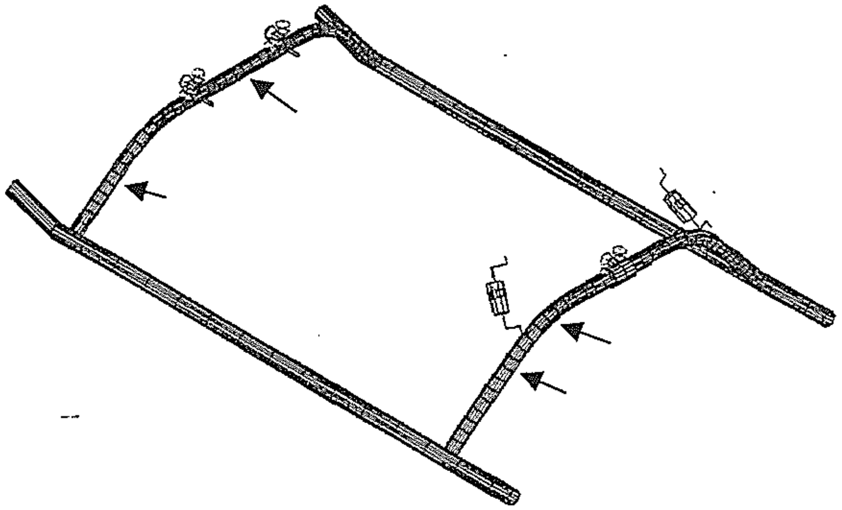
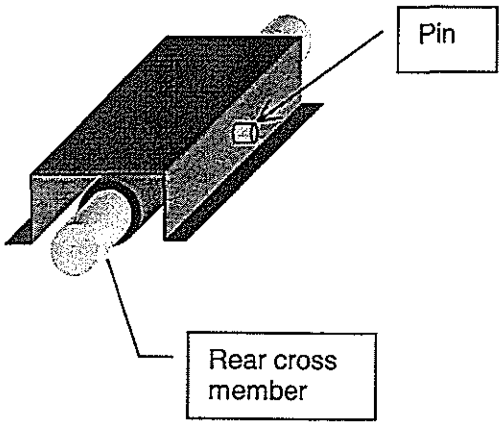


**Fig. 1-The skid landing gear complete model**

The forward cross member is constrained by clamps in two points, substantially allowing relative translation and rotation around and along the tube axis in its central straight part. Rings housed on the tube itself prevent sliding along the tube axis.



The more massive rear member is constrained in one point only, in the middle, where the tube is strengthened by a thickening reinforcement and connected by a pin to a hat shape case (Fig. 2).

Two axial viscous dampers are set between the rear cross members and the fuselage. Though dampers were introduced to prevent ground resonance, they play a significant role in landing performance. Modifications in their characteristics, location or alignment affect overall landing performances and loads introduced in the fuselage structure.

**Fig. 2-Rear cross member constraint to fuselage**

In the numerical multi-body model, the cross members and the skids are modelled with elasto-plastic *beam* elements (Fig. 3), while the fuselage body is retained as rigid, with its mass lumped in its centre of gravity. The simulations carried out, for validating the model, reproduce the drop tests where equivalent mass was used.

A total of 60 masses and 60 *beam* element are used to model skids and cross members. Cross members typical *beam* length is about 115 mm.

Nodes assigned to the fuselage rigid body are used to define the position of constraints and damper-fuselage attachments. Cross member constrains are modelled by single point elastic joints (*point* elements).

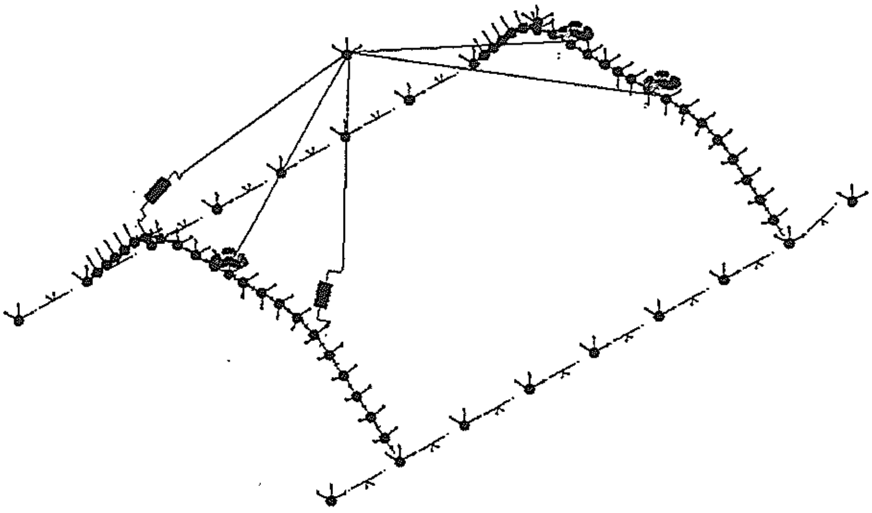


Fig. 3 - Multi-body mass and elements frame

Reactions are considered negligible in forward member constraints for a translation along tube axis in its straight part and a rotation around the same axis, as well as in rear member constraint for a rotation around the pin axis. The corresponding *point* elements leave these motions completely free.

Contacts are modelled in VeDyaC by using contact elements. They are characterised by geometrical characteristics and by two main contact properties: contact volume and contact pressure [4]. The contact behaviour depends upon the relative properties of interacting elements. Hysteresis and friction can also be introduced. Available shapes are cylinders, spheres, polyhedrons and plans. The gear frame is entirely coated by *cylinder* contact elements (Fig. 1). There are *polyhedron* elements to activate the contacts between the rear cross member and the case (Fig. 2) and the lateral contact between anti-slide rings and forward member clamps.

Multi-body models data can easily be ordered in separated assemblies. As each assembly defines a local reference frame, their relative positioning is straightforward. This feature has been widely used to easily reproduce different landing attitudes and conditions.

## 3 - Characterisation Procedures

To complete the definition of the model, elasto-plastic beams properties, dampers viscous behaviour and constraints stiffness had to be defined. The skid-soil contact was characterised by simple assumptions and tuned in a later phase.

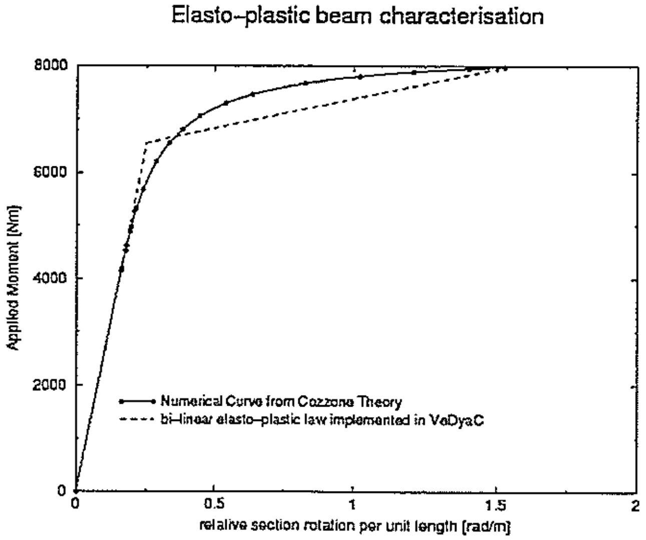


Fig. 4- bi-linear elasto-plastic beam section characterisation

Non-linear elasto-plastic bending behaviour was reproduced basing on the application of Cozzone's theory [8]. This procedure was available from the early design stage of the skid landing gear. It was used to characterise separately the cross member in order to define their diameters and optimal tapering laws along members axis.

As a fine description of the material stress-strain curve was used, numerical bending curves derived by Cozzone's theory implementation describe quite accurately plastic beam bending.

Elasto-plastic elements in VeDyaC are defined by bi-linear generalised force-displacement laws; hence the original curve had to be approximated with a bi-linear law by identifying a yielding point.

Taking in account the expected moment maximum values, available from early design phase predictions, the yielding point was set in correspondence of a stress value on the outer fibres about 3% higher than 0.2% yield strength. Fig. 4 shows an example referred to a section in the rear cross member.

A new type of elastic-plastic law, where plastic curve can be given more accurately, has been recently made available in VeDyaC. Considerations about the opportunity to utilise this new law will be presented later.

Dampers were characterised by their Force vs. velocity curve.

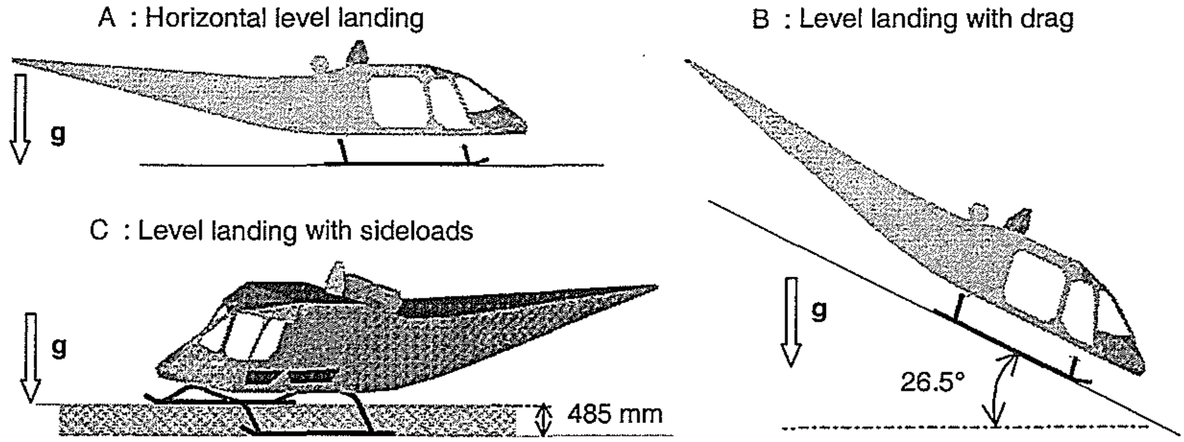
Skid gear attachments to fuselage modelled by *point* elements needs a stiffness characterisation. The analyses showed a negligible sensitivity of results to these parameters, provided that relative displacements between cross members and the rigid modelled fuselage are very small. For this reason, very stiff elastic properties were assigned to all restrained dof. Only the torque stiffness in rear cross member attachment was evaluated by a more accurate calibration, allowing for warping restraint [9].

Skids-soil contact was initially characterised by imposing conditions arising from following considerations:

- No deformation on skid surfaces was expected.
- A ground towing test was performed to evaluated friction on the same soil to be used in drop test (a tread plate laid over a concrete floor to reproduce a very rough ground). Low-velocity sliding friction was found to be about 0.40.
- After a rough estimation of vertical ground reaction distribution, a maximum penetration of 2 mm into soil was used to calibrate contact properties.

## 4 – Drop Tests and Simulation Results

Three main drop tests were carried out in level landing conditions at Augusta Laboratories, namely horizontal level landing, level landing with drag and level landing with lateral loads. Test were designed to reproduce the load conditions required by regulations [1]. Fig. 5 exemplifies drop test conditions.


A : Horizontal level landing

B : Level landing with drag

C : Level landing with sideloads

**Fig. 5-Drop tests conditions**

All drop tests were performed at 2 m/s sink speed, with an equivalent mass evaluated by assuming a rotor lift correspondent to the two-thirds of maximum design weight. The data acquisition system consisted of more than 20 measuring devices for each drop condition:

- Triaxial accelerometers, at centre of gravity and in two different locations with offsets along roll and pitch axis.
- LVDT potentiometers for measuring deflection of forward and rear member and the displacement of the equivalent mass centre of gravity.
- Two load cells housed in forward cross member clamps.
- Load cells and LVDT potentiometers to measure load and stroke of dampers.
- Strain gauges couples located on the forward and rear cross members and on the skids.

Acquisition was performed at 1000 Hz sampling frequency.

The previously described model attained an appreciable result (Fig. 6). Numerical vs. experimental data comparison is based on the load transmitted to fuselage by one the forward cross member, as it was acquired by the load cells housed in the forward member constraints. These signals are more suitable to be confronted with model solution outputs, as the release mechanism introduced a disturbance into accelerometers experimental signals, imposing the use of a low-pass filter.

The simulation result reproduces with good accuracy the loading ramp and the maximum value. Model solution configures a somewhat smoother curve and predicts an unloading ramp anticipated with respect to the experimental data. Furthermore load peaks are overestimated during the very first instants of the impact.

To improve the correlation between the two curves, a skid-soil contact tuning was performed. Histeresys phenomena was supposed to occur in the first instants, contact pressure was forced to grow more rapidly, and friction was decreased, allowing for a dynamic reduction effect with respect to the low-velocity towing test (from 0.40 to 0.30). The maximum penetration resulted substantially unchanged. The new curve is reported in Fig. 7.

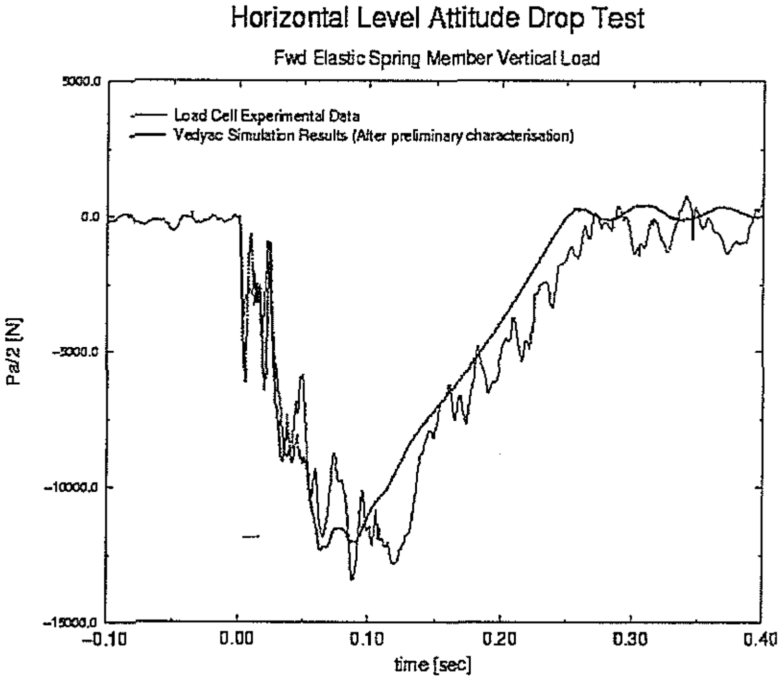


**Fig. 6- Numerical vs. experimental loads in the forward cross member constraint with the original characterisation of soil properties in the model (cond. A)**

The curve obtained after calibration follows very well the time history of load transmitted by forward cross member to fuselage. This is particularly true for the loading ramp, while the rebound phase is not perfectly reproduced, though overall impact duration is well predicted.

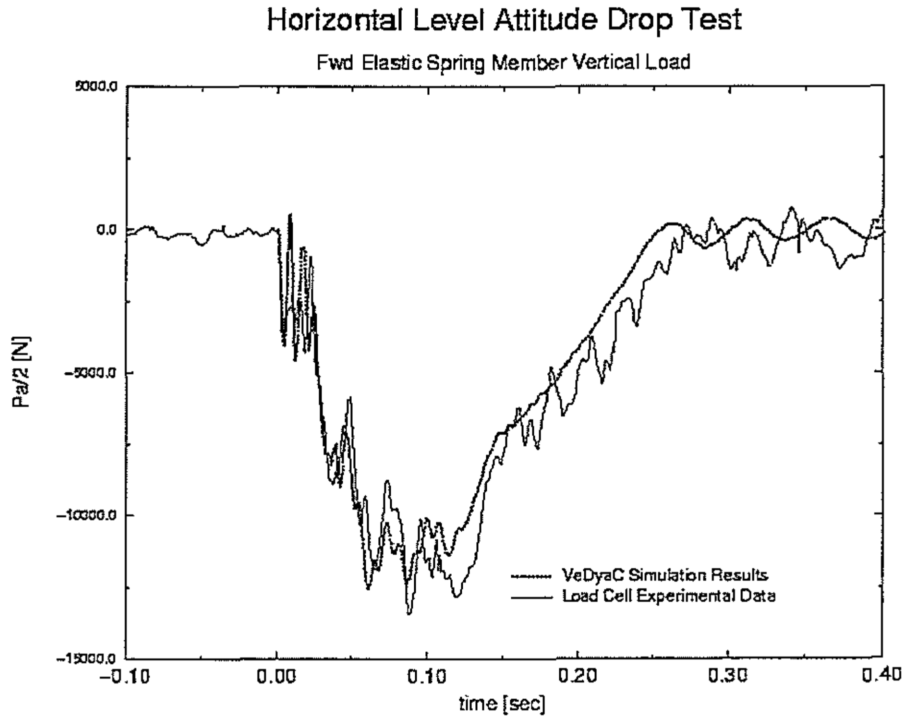


**Fig. 7-Numerical vs. experimental loads in forward cross member constraint after skid-soil contact tuning (cond. A)**

Fig. 8 reports numerical vs. experimental data for vertical acceleration in the horizontal drop simulation and test.

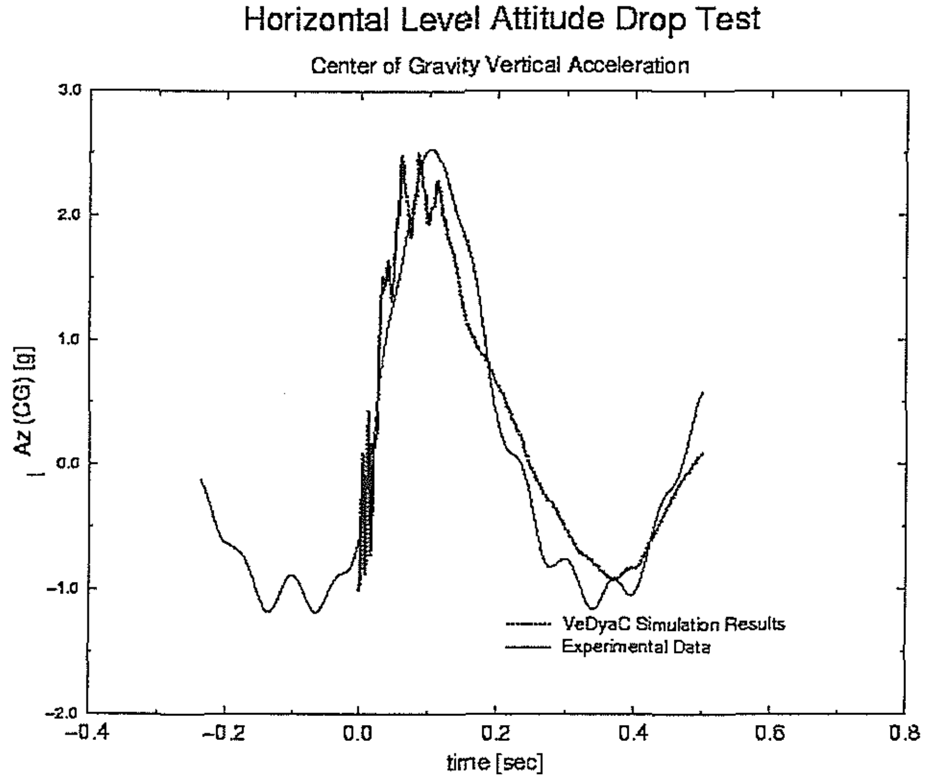


Fig. 8-Numerical and experimental CG vertical accelerations (cond. A)

Though the filtering of experimental curve does not allow detailed considerations, the error on maximum value of deceleration is limited to 2.4%. Table 1 indicates the percentages error between measured displacement and model solution.

Damper behaviour is also very well reproduced, particularly up to the onset of the rebound phase (Fig. 9).

**Tab. 1: Numerical vs. Experimental percentage error for maximum CG displacement and cross members deflection (Horizontal level drop test)**

| Location | %Δ |
|---|---|
| CG displacement | +1.12% |
| FWD cross member | +0.5% |
| AFT cross member | -1.7% |

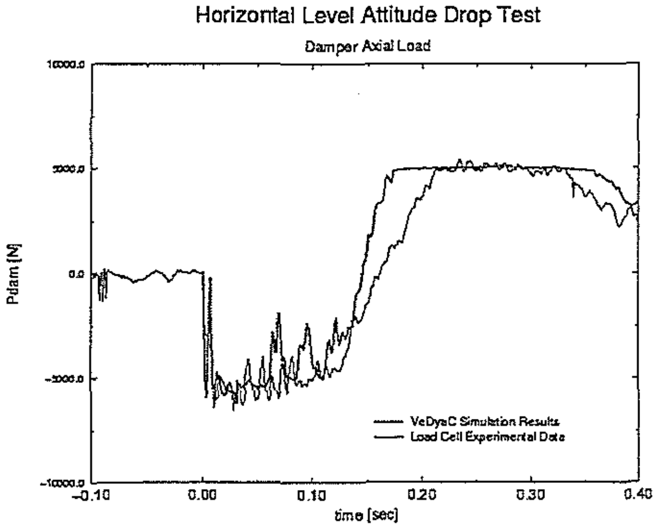


Fig. 9- Numerical and experimental damper loads

No further modification were introduced to simulate the other drop conditions. Fig. 10 to 12 report the results for the load in one of forward member constraints, as well as CG acceleration along Z and X helicopter body axis, for the simulation of landing with drag attitude (cond. B- Fig. 5). Fig. 14 is referred to CG displacement measured in a fixed reference frame and allows for the sliding along the inclined plane.

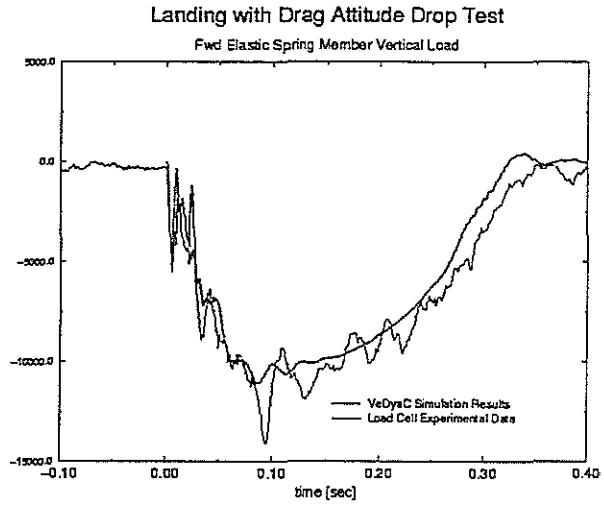


Fig. 10 - Load in forward member constraint (cond. B)

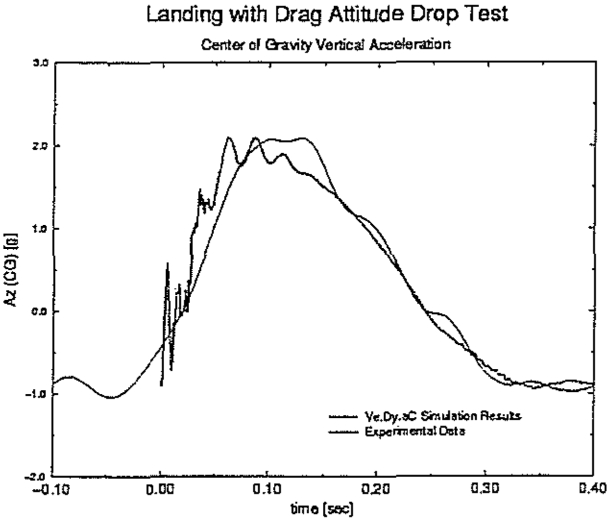


Fig. 11-Helicopter vertical axis acceleration (cond. B)

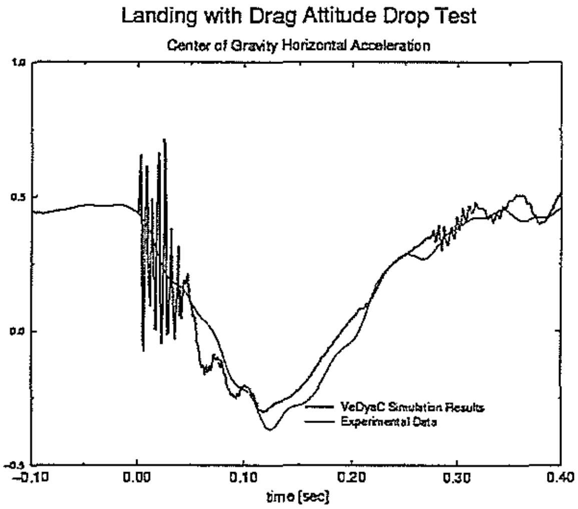


Fig. 12 -Helicopter roll axis acceleration (cond. B)

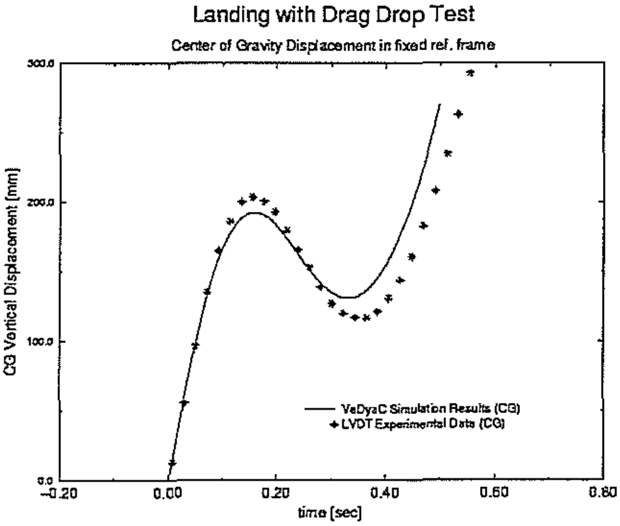


Fig. 13-Vertical displacement (cond. B)

Acceleration maximum values and pulse widths are well reproduced. The narrow load peak in the forward member load is not completely developed, but, as for the horizontal landing case, the loading ramp phase shape indicates that most of the details of the structural response are represented by the model with good numerical approximation. The picture in Fig. 14 shows the deformed shape of the skid landing gear in this condition.

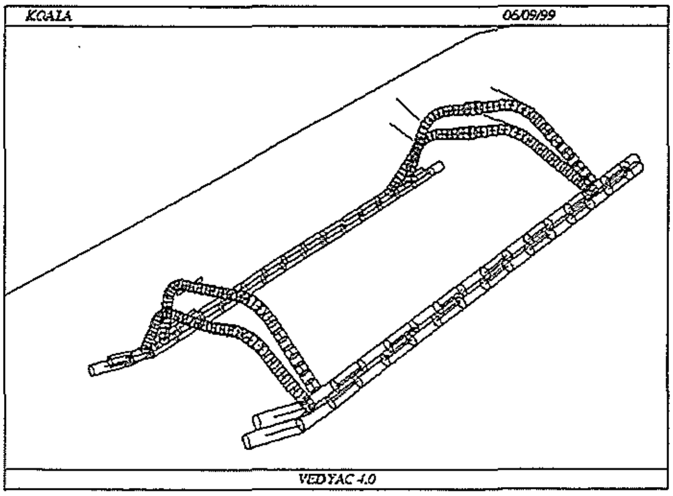


Fig. 14-Deformed shape in landing with drag attitude (cond. B)

Results for landing with lateral loads (cond. C - Fig. 5) are presented in Fig. 15 to 18. Fig. 15 and 16 are referred to acceleration along Z and Y helicopter body axis. Fig. 17 and 18 reports numerical vs. experimental data for the load cell housed in both forward cross member constraints to fuselage.

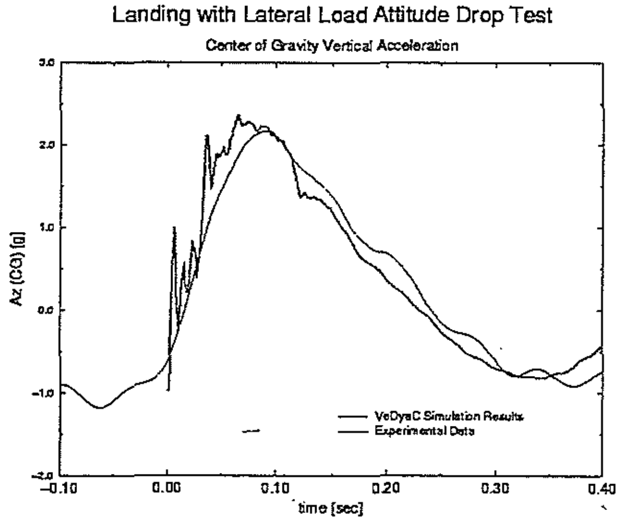


Fig. 15- Helicopter vertical axis acceleration (cond. C)

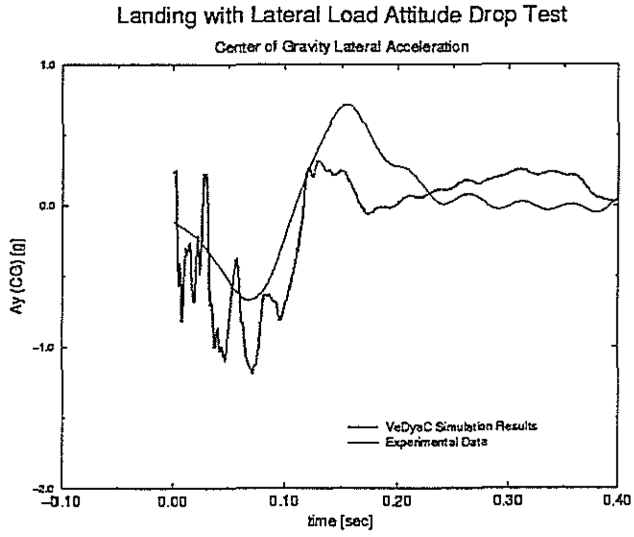


Fig. 16- Helicopter pitch axis acceleration (cond. C)

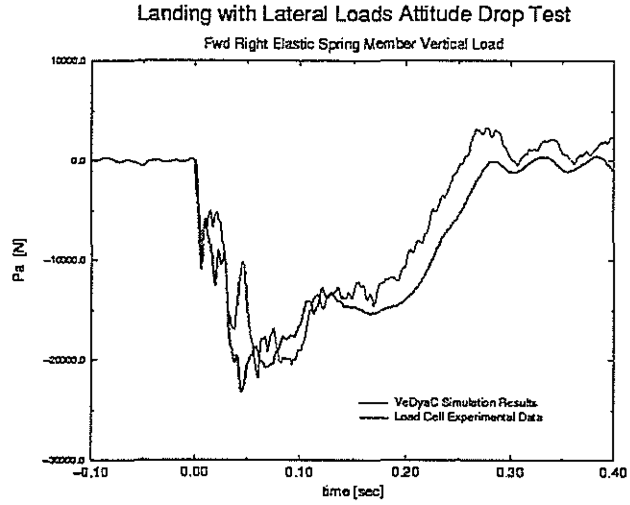


Fig. 17- Load in forward member left constraint (cond. C)

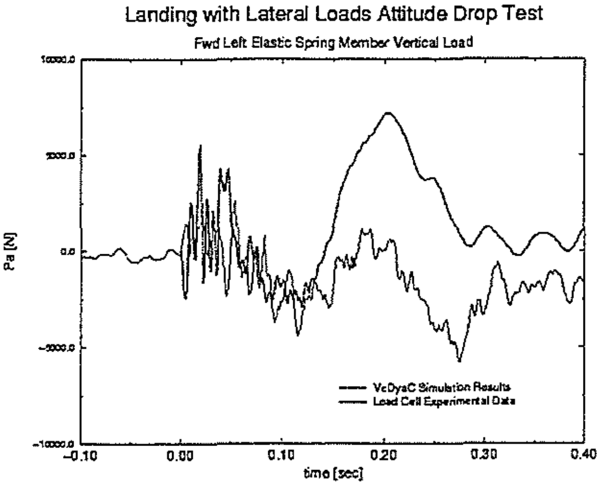


Fig. 18- Load in forward member right constraint (cond. C)

The load in the left constraint (Fig. 17) is up to 100% higher than in the horizontal level drop test (Fig. 7). The model reproduces its time history with good accuracy. The load in the other constraint is one order of magnitude lesser up to the rebound phase. This is as well reproduced by model solution (Fig. 18), though discrepancies between the model and the test are in this case evident during the rebound phase of the impact.

Fig 15 shows that the error on the maximum value of deceleration is limited to 5%.

The contact between the rear cross member and the upper hat case never became active in the simulations. This is in accordance with experimental evidence.

The evaluation of strain in the cross member is partially affected by the reduction of their bending behaviour to a bi-linear elasto-plastic law. Equivalent numerical strains were evaluated by the moment in the *beam* elements and then compared with the data acquired by the strain gauges couples in the correspondent locations (Fig. 1). Fig. 19 and 20 are referred to horizontal level landing conditions (cond. A).

Fig. 19 is referred to a location on the forward member inclined terminal part. The element has not experienced plastic strain during the simulation. The reproduction of strain gauges data is satisfactory. Fig. 20 is referred to the central and most loaded portion of forward cross member. Plastic strain occurs, thus showing a different behaviour from the strain gauges experimental data. The inadequate characterisation of *beam* elements can give reason for most of the discrepancies between model and experimental data. A better result could surely be attained by a more accurate representation of the bending behaviour, now available in the solver code.

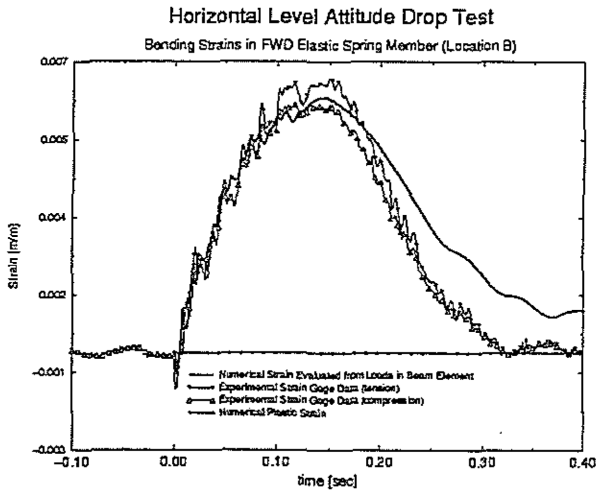


**Fig. 19** – **Numerical vs. experimental strain Location B (cond. A)**

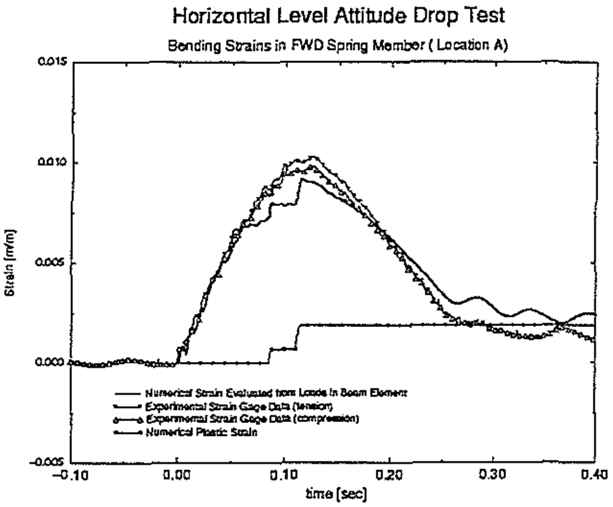


**Fig. 20** – **Numerical vs. experimental strain Location A (cond. A)**

The simulations results, in drop test conditions, shows that both overall landing performance, as well as load transmitted to fuselage can be reproduced with a noticeable accuracy by the model which can be considered suitable to attain reliable prediction in conditions not reproduced by drop test.

The time required for model solution is extremely short, as a 0.5 seconds long simulation takes only 235 CPU seconds time on an Alphastation 600A 5/500.

## 5 – Model Predictions in Different Landing Conditions

Some results are here presented to allow an evaluation of landing gear behaviour as well as the capabilities of this kind of model.

Friction is a critical parameter in the performance of the skid landing gear. Drop test conditions were performed with a rough soil in order to attain a high friction coefficient and hence a high load factor, but low friction implies higher deflections of cross members and increases the arms of ground reactions.

**Table 2: Percentage Variations of Maximum Displacements and loads acting in cross members for three friction coefficients**

| Friction Coeff. | 0.40 | 0.25 | 0.10 |
|---|---|---|---|
| CG displacement [mm] | 171 | 186 | 202 |
| Moment (loc. A )[N m] | 6985 | 6997 | 6974 |
| Moment (loc. C )[N m] | 6939 | 7116 | 7312 |
| Moment (loc. D)[N m] | 8279 | 8456 | 8633 |

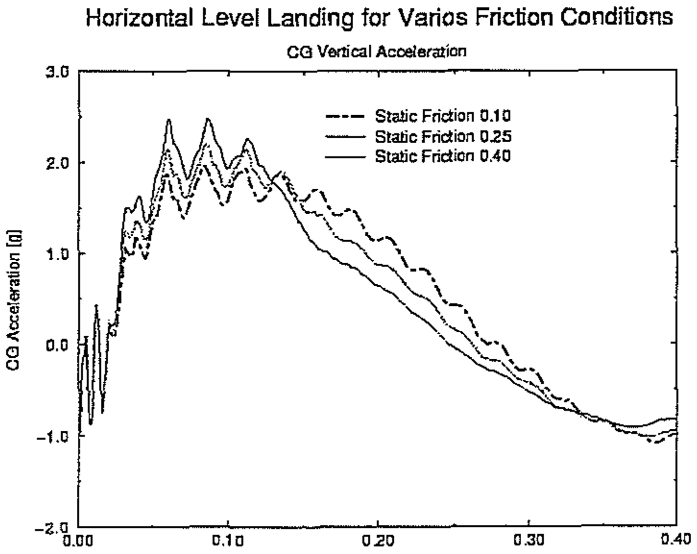


**Fig. 21** – **CG vertical accelerations at various soil friction conditions**

Two simulations were carried out in horizontal level landing attitude, with frictions parameters equivalent to 0.10 and 0.25 static friction coefficients. Table 2 indicates the variations in the values of maximum CG vertical displacement and in moments in three locations of cross members (Fig. 1) with respect to drop test simulations. Fig. 21 compares the accelerations in the three conditions.

The simulation with the lowest friction coefficient (0.10) predicts a maximum CG deflection of about 20% more than the level horizontal drop test conditions (cond. A). This deflection does not imply any clearance problem.

The moments in the cross members are generally increasing as the friction factor decrease. This tendency is evident in rear cross member. As far as the forward cross member is concerned, the behaviour is different and the moment does not show a remarkable increase. This is due to the uniform bending load acting along its central straight part, which produces a diffused moderate plastic strain and increase the cross member efficiency.

Performance in limit conditions at different landing weights were evaluated by introducing in the model an averaged rotor lift equal to the two third of the landing weight.

Simulations at various landing weights measure the increasing in load factor at diminishing weights, as it is showed in Fig. 22. The landing gear stiffness remains unchanged while the weight and the energy to be absorbed decrease, thus leading to higher load factors. Ground reactions decrease but the forward cross member shows a tendency to reach a maximum typical load (Fig. 23).

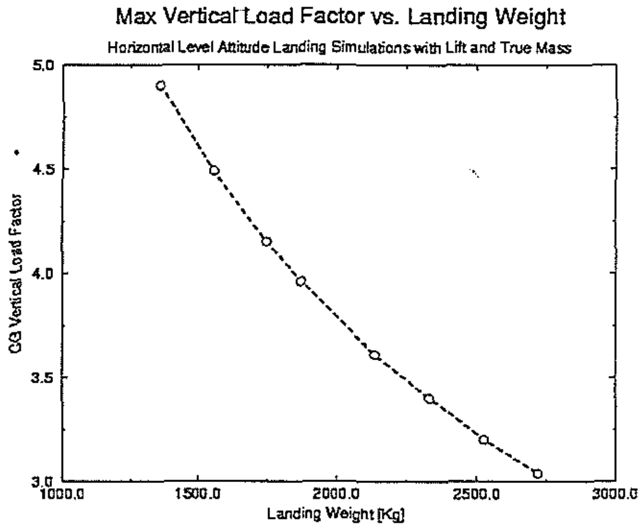


**Fig. 23 – Maximum vertical load factor vs. landing weight (horizontal level attitude)**

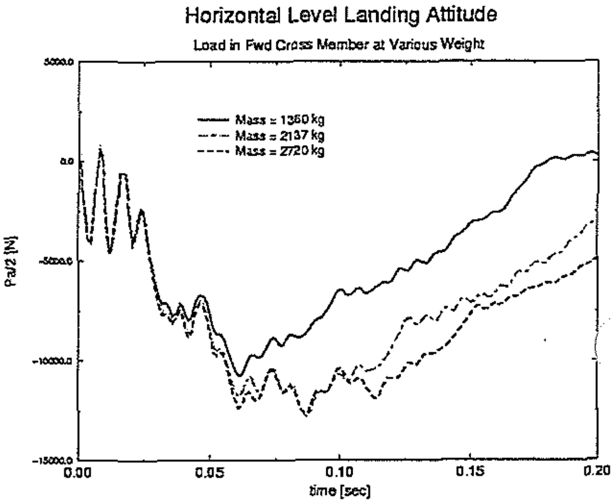


**Fig. 24 – Load in forward member right constraint at various landing weight (horizontal level attitude)**

Finally a simulation in a particular soil condition is presented. A landing was simulated in case of lateral obstruction. Friction coefficient and sink velocity were the same as in drop test conditions. The obstruction consisted of a very stiff contact element placed parallel at the skid, along one third of its length. Contact was set to occur immediately after the impact.

No remarkable increasing in vertical load factor was detected, but side acceleration was found to be higher than for the landing with lateral load condition (Fig. 22). Fig. 23 is referred to the instant of maximum deflection.

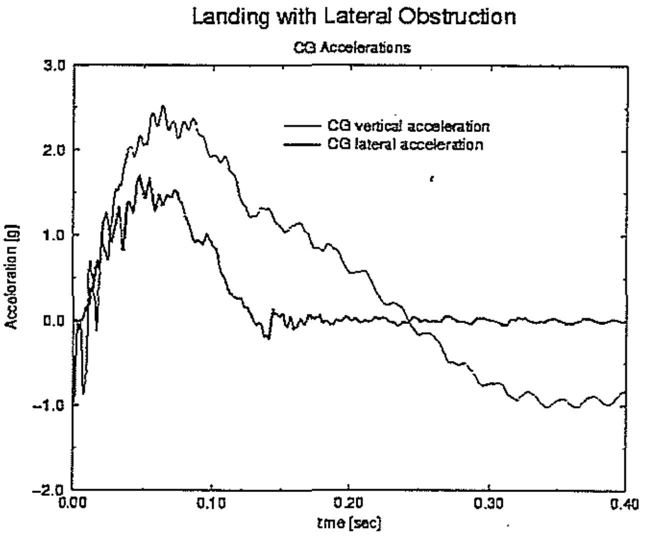


**Fig. 22 – CG accelerations for landing with lateral obstruction**

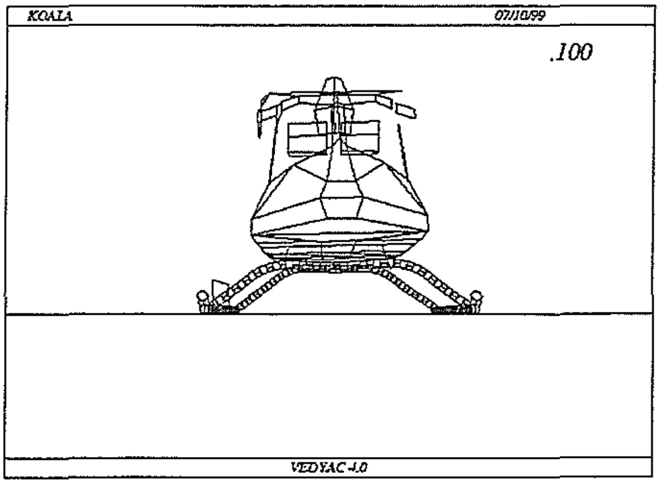


**Fig. 23 – Maximum deflection in landing with lateral obstruct**

## 6 - Concluding Remarks

Results attained by the multi-body approach in simulating limit landing condition can be considered very appreciable. Modelling required a correct evaluation of structural behaviour of the landing gear components and of constrains with fuselage. Most of the modelling effort was dedicated to the characterisation of elasto-plastic beam behaviour, but, as a matter of fact, even the apparently simpler classical approach, based on separated modelling of cross members, requires the same accuracy if reliable results have to be attained.

The landing performances for a skid landing gear are appreciably influenced by the soil properties, particularly by the skid-soil friction. In this case, a tuning of the soil contact properties was performed taking in account the experimental data. However, the curve in Figure 6 has shown that good results can be achieved by characterising soil with reasonable assumptions and performing, if needed, some tests to evaluated the friction in soil conditions to be used for design and testing.

The time required for a simulation, as well as the very little modifications needed to simulate different landing attitudes and soil conditions, indicates that this approach should be considered suitable to be used from the very earliest design phases. The simulation results should be even improved by characterising with a more accurate law the cross member elasto-plastic behaviour.

This case, as the model was developed after the design phase was concluded, can be considered a workbench at this regard.

Besides the overall landing performance, attention was focused on predictions regarding dampers behaviour and loads transmitted to the fuselage. Thanks to the exhaustive amount of data collected during the drop tests, these prediction have been compared with experimental data, showing good correlation for all the three attitudes taken into consideration.

The present results, together with the works by Astori [5,6 and 7], shows that a multi-body approach can be usefully applied to performance prediction and design of skid and wheels landing gear both in emergency and limit landing conditions.

## References

1. FAA, FAR part 27, Airworthiness Standards: Normal Category Rotorcraft, 1998.
2. Max Chernoff (Republic Aviation Corporation -USA), Analysis and Design of Skid Gears for Level Landing, Journal of American Helicopter Society, 1962.
3. V. Giavotto, L. Puccinelli and M. Borri (Politecnico di Milano-Italy), Vehicle Dynamics and Crash Dynamics with Minicomputers, Computers & Structures, Vol. 16, No 1-4, pp. 381-393, 1983.
4. L. Puccinelli (Politecnico di Milano-Italy), Modelli di Contatto nei Programmi per la Simulazione di Crash (in Italian), Atti del X congresso Nazionale AIDAA, Pisa 16-20 Ottobre 1989.

5. P. Astori (Politecnico di Milano-Italy), Multi-Body Simulations for Helicopter Crasworthiness and Experimental Results, 22nd European Rotorcraft Forum, 17-19 Sept. 1996.
6. P.Astori (Politecnico di Milano-Italy), Full-Scale Helicopter Crash Landing Test and Multi-Body Analysis, International Crashworthiness Conference IJCRASH'98, Dearborn (MI, USA), 9-11 Sept. 1998.
7. P.Astori (Politecnico di Milano-Italy), M. Ignarra and S. Poggi (Agusta, a Finmeccanica Company-Italy), A129 Crash Test and Simulation, 24th European Rotorcraft Forum, Marseille (F), 15-17 Sept. 1998.
8. F.F. Bruhn, Analysis and Design of Flight Vehicles and Structures, S.R. Jacobs and Associates, Indianapolis (USA), 1973.
9. C. Young Warren, Roark's Formulas for Stress and Strain, 6th edition, Chap. 9, art. 9.3, Mc Graw Hill International Edition, 1989.
10. A. Barsony-Nagy and R. Rivlin (Mata Helicopters – Israel), Simulation of helicopter landing on a ship deck, Collection of Papers of the 30th Israel Annual Conference on Aviation and Astronautics, 1989.